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ARTICLE

Creep Behavior of CP-Ti TA2 at Low Temperature and Intermediate Temperature

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Abstract: Significant temperature and stress dependent creep behavior of commercial pure titanium TA2 was observed at low and intermediate temperature. According to the variation of creep strain with applied stress level, the relationship between threshold stress level and the corresponding creep temperature was determined. Based on short time creep tests, the constitutive equation containing steady state creep strain rate was used to extrapolate the minimum creep rate. The existence of steady state creep of commercial pure titanium TA2 was confirmed by subsequent long time creep experiments. Through the minimum creep strain rates, creep stress exponent was obtained which also indicates the accuracy of the extrapolated minimum creep strain rates. The activation energy of primary creep (approximately 60 kJ/mol) at different creep strains level was higher than the activation energy for slip controlled creep, which demonstrates the importance of twinning for the development of creep behavior of TA2 at low temperature. Moreover, according to the variation of twinning structure with deformed temperature in creep tested specimens, the temperature dependent creep behavior was interpreted and the importance of twinning for creep behavior of TA2 was confirmed.

Key words: commercial pure titanium TA2; threshold stress; steady creep; activation energy; twinning

Low temperature creep can be understood as time-dependent plasticity that occurs at $T<0.3T_m$ and at stresses below the macroscopic yield stress. Compared to high temperature creep, materials generally neither fail nor experience significant plasticity due to low temperature creep[1], and thus relatively less attention has been paid to low temperature creep. It has been reported that low temperature creep occurs in many materials, such as CP-Ti [2-8], titanium alloys[9,10], steel[11], copper[12-14], magnesium alloys[15], silver[16]. Among them, CP-Ti, Ti-6Al-4V, pure magnesium and AZ31 display marked creep deformation. Oberson[17] suggested that slip and time-dependent twinning were active deformation mechanisms for low temperature creep behavior of HCP *α*-Ti-1.6wt%V. The mixed slip and twinning deformation mechanisms which caused low temperature creep of α titanium alloys was also proposed by Wyatt[18]. In low temperature creep tests the steady creep rate stage and the third stage of many materials were not observed, so low temperature creep is a discussion of primary creep[1]. Since the steady-state creep strain rate is an important quantitative measure of creep behavior, extrapolation is efficient to obtain the minimum creep rate based on creep tests data in short time[4,5,15,19,20]. However, Peng et al.[6] found that the steady state creep rates extrapolated by different experimental times were different and suggested that only primary creep stage exists in the low temperature of CP-Ti during short experimental time. Obviously, the apparent steady state creep stage of CP-Ti has not been observed in previous work and whether the secondary steady creep exists or not in the low temperature creep behavior is worthy discussing. Thus, in the present paper the creep behavior of CP-Ti at low and intermediate temperature will be investigated.

1 Experiment

The material used in this investigation was TA2 and its chemical composition is given in Table 1. Rectangular cross sections specimens were used with 100 mm length, 10 mm width and 3 mm depth. The detailed experimental scheme

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Table 1 Chemical composition of TA2 (wt%)

Ti	Fe	C	N	H	O
>99	0.06	0.01	<0.01	0.001	0.12

Table 2 Experimental scheme

Stress level	Temperature/K					
($\sigma/\sigma_{0.2}$)	573	498	423	388	353	293
1.2	√					
1.06			√		√	√
1.0	√	√	√	√	√	√
0.92			√		√	√
0.85			√		√	√
0.7			√		√	√

is listed in Table 2. Room temperature was adjusted by air conditioning in the laboratory and creep test temperature was controlled by high temperature furnace of creep testing machine. The temperature controlled error was ±1 K.

2 Results and Discussion

According to the experiment approach, these creep tests were conducted to obtain the creep curves of CP-Ti at the temperature of 293~573 K and under different stress levels, as shown in Fig.1.

2.1 Significant temperature and stress dependent creep behavior

Obviously from Fig.1, the creep behavior of TA2 at low and intermediate temperature is closely related to temperature and stress. When creep temperature is constant, creep strain increases with creep stress and creep strain accumulates very slowly at a relatively lower stress level. Thus, the creep behavior will not occur in case of stress lower than the threshold stress. At 423 K, creep strain increases quickly at the first 10 h, then the phenomenon of creep saturation is observed and the time to reach creep saturation shortens with stress decreasing. Zhang et al.[8] suggested that creep saturation was related to the rapid creep exhaustion rate at primary stage. Guo et al.[15] determined the threshold stress of Mg-2Nd-0.5Zn-0.4Zr alloy in creep according to linear relationship between creep strain and the applied stress level. Peng et al.[6] indicated the range of threshold stress of CP-Ti at low and intermediate temperature, as shown in Table 3.

The value of creep strain after approximately 40, 80, 120, 160, 200 h, was plotted against various stress level as shown in Fig.2. The relationship between creep strain and the applied stress level is linear, expressed as:

$$\varepsilon = 0.171401(S - 0.765287) \quad (1)$$

Similarly, threshold stress at other temperatures could be obtained by this method, as shown in Table 4. Also threshold stress in Table 4 is consistent with that in Table 3. According to threshold stress level S in Table 4, threshold stress level against the corresponding temperature is plotted in Fig.3.

It can be seen that the relationship between threshold stress level S and creep temperature meets quadratic equation, as follows:

$$S = 0.000011T^2 - 0.009673T + 2.628306 \quad (2)$$

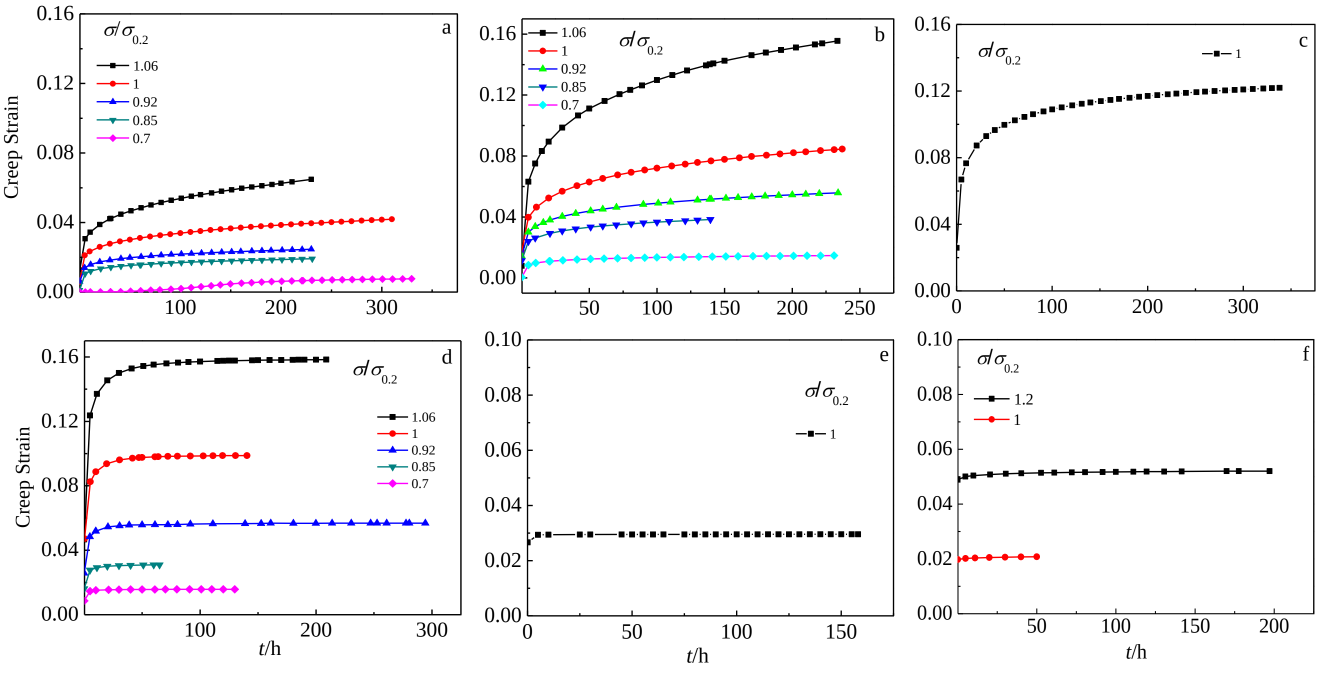

Fig.1 Creep curves of TA2 under different deformation conditions: (a) 293 K, (b) 353 K, (c) 388 K, (d) 423 K, (e) 498 K, and (f) 573 K

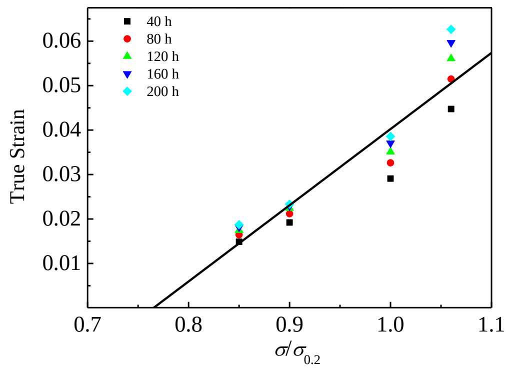

Fig.2 Creep strain versus applied stress level at room temperature

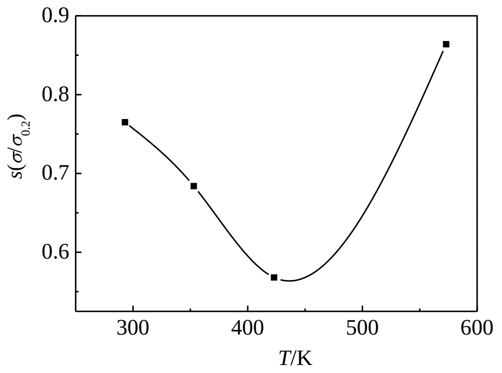

Fig.3 Relationship between threshold stress level S and creep Temperature

Table 3 Range of threshold stress level (S) of CP-Ti at 293~423 K[6]

Temperature/K	293	353	423
S (Stress level)	0.7~0.85$\sigma_{0.2}$	0.6~0.7$\sigma_{0.2}$	0.5~0.6$\sigma_{0.2}$

Table 4 Threshold stress level (S) of TA2 at 293~573 K

Temperature/K	293	353	423	573
S (Stress level, $\sigma/\sigma_{0.2}$)	0.765	0.684	0.568	0.864

2.2 Results analysis for short time creep experiment

At low creep stress and creep strains, the primary creep deformation of many metals and alloys can be described by a logarithmic creep law. In case where there is larger accumulation of primary creep strains, the deformation often can be described by a power law [10].

Therefore, at 293~353 K when low temperature creep behavior is apparent, steady state creep strain rate can be extrapolated by power law constitutive equation, as follows:

$$\varepsilon = \varepsilon_0 + \beta t^n + \dot{\varepsilon} t \quad (3)$$

where ε is total true strain, ε_0 is instantaneous loading strain, t is the creep time, and $\dot{\varepsilon}$ is the extrapolated minimum creep rate. At 423~573 K, creep behavior is apparent in the first few hours, and then creep strain accumulates slowly. Thus, a logarithmic creep law is appropriate to extrapolate $\dot{\varepsilon}$ of TA2 at 423~573 K, as below:

$$\varepsilon = \varepsilon_0 + a_1 \ln(1 + a_2 t) + \dot{\varepsilon} t \quad (4)$$

However, according to creep data within 300 h, most of the extrapolating $\dot{\varepsilon}$ are negative values, meaning creep behaviors do not show steady state characteristic in short time tests. In order to verify the existence of steady state creep, long time creep experiments were conducted.

2.3 Results analysis for long time creep experiment

In this section, two relatively long creep experiment were conducted, including: (1) T=293 K, stress level $S(\sigma/\sigma_{0.2})$=1, t=2000 h. (2) T=353 K, stress level $S(\sigma/\sigma_{0.2})$ =1.06, t=1000 h. Two sets of relatively long time creep curves are shown in Fig.4.

From Fig.4, it can be seen that at 293 K after approximately 1000 h, creep strain rate fluctuates at the value of $10^{-5}h^{-1}$. At 353 K after 1000 h, proper steady state creep has not appeared in the test, and the creep rate keeps ever-reduced.

2.3.1 Discussion of steady state creep at 293 K

The constitutive model viz. Eq.(3) are used to extrapolate the minimum creep rates of different creep times and the parameters are listed in Table 5.

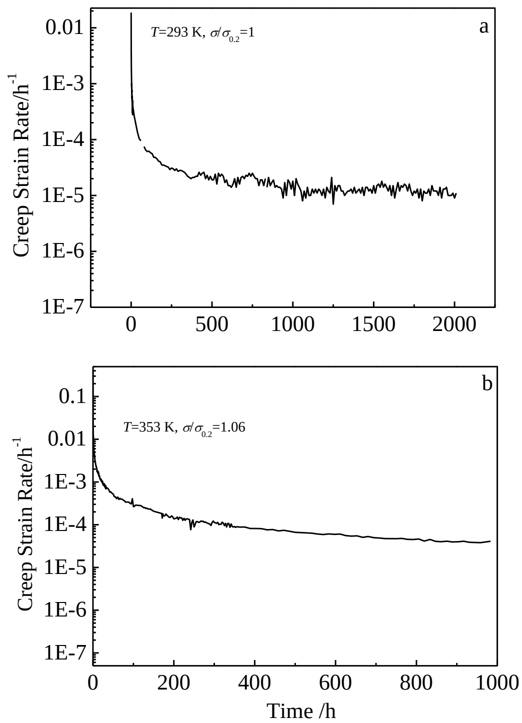

Fig. 4 Creep strain rate versus time of long time creep tests: (a) t=2000 h and (b) t=1000 h

Table 5 Extrapolated steady state creep rates of different creep times

t/h	β	n	$\dot{\varepsilon}$ /×10^{-4} h^{-1}
10	0.016540	0.164168	-0. 80
100	0.016319	0.15980	-0. 040
250	0.016374	0.155307	0. 060
500	0.016379	0.155044	0. 060
1000	0.016459	0.151616	0. 080
1500	0.016384	0.152410	0. 080
2000	0.016403	0.153672	0. 080

As can be seen from the above data in Table 5:

(1) The fitted power law parameters of β and n based on different creep times are almost the same. The extrapolated steady state creep strain rates are negative based on creep data of 10 and 100 h, which means creep behavior is primary creep in 100 h. Thus, with creep data within 100 h, the primary creep can be described as follows:

$$\varepsilon = 0.016318t^{0.159273} \quad (5)$$

(2) The extrapolated steady state creep strain rates based on different creep time are different. Here, as shown in Fig.5 and Fig.6, creep strain rate versus time are plotted.

Obviously, the overall trend of creep strain rate during 250~500 h is decreasing, while creep strain rate fluctuates up and down after 1000 h, which is approximately equal to 10^{-5} h^{-1}. Therefore, initial 500 h creep is still in the first

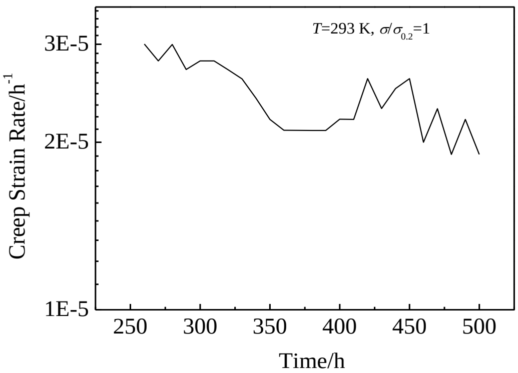

Fig. 5 Creep strain rate during 250~500 h

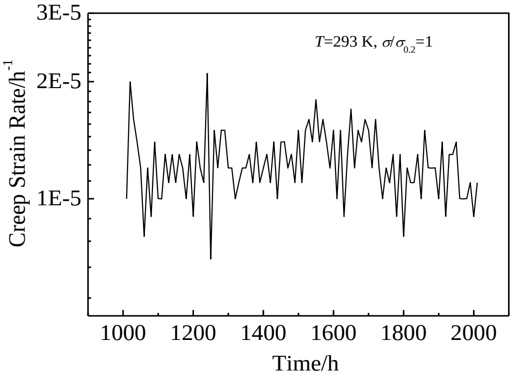

Fig. 6 Creep strain rate during 1000~2000 h

stage and after 1000 h the steady state creep appears. If the first creep stage is very short and the second stage is the main part of creep curve, then the extrapolated steady state creep strain rate will be a constant as the primary creep strain item(βt^n) in Eq.(3) can be neglected. Thus, there is a difference between the extrapolated creep strain rate before 500 h and that after 1000 h.

(3) In order to accurately calculate the steady state creep rate after 1000 h, creep data during 1500 h to 2000 h is used. As in this period creep behavior is the steady state creep, a liner equation is used to obtain the minimum creep rate, as follows:

$$\varepsilon_{\text{total}} = \dot{\varepsilon}(t\text{-}1500)+\Delta\varepsilon_{1500} \quad (6)$$

where $\Delta\varepsilon_{1500}$ is the creep strain before 1500 h. Fitting results are as follows:

$$\varepsilon_{\text{total}} = 1.2\times10^{-5}(t-1500)+0.061627 \quad (7)$$

Therefore, the minimum creep rate is 1.2×10^{-5}h^{-1}. On the other hand, if creep behavior during 1000~2000 h is not the second stage, then creep behavior can be described with power law. With creep data during 1000~2000 h, the primary creep is expressed as：

$$\varepsilon = 0.006647t^{0.304863} \quad (8)$$

The parameters β and n are independent of time; however the parameters β and n in Eq.(8) are much different from parameters in Eq.(5), and this also means after 1000h creep reaches to the second stage.

2.3.2 Discussion of steady state creep at 353 K

From Fig.4b, it can be seen that creep strain rate has dropped apparently before 300 h, power law is proper to describe creep behavior. After 300 h, the power law containing steady state creep rate is used to extrapolating the minimum creep rate and the extrapolated results with different time is listed in Table 6.

Based on creep data within 500, 800, 1000 h, all of the extrapolated $\dot{\varepsilon}$ are negative values, which means when creep experiment up to 1000 h, creep behavior is still at the primary stage. The extrapolated parameters of β and n based on different time are same, which also means within 1000 h creep is primary creep.

From the discussion mentioned above, it is clear that at 293 K and stress level of 1, after 2000 h the minimum creep rate was obtained. Thus, the secondary stage creep of TA2

Table 6 Extrapolated results with different time

t/h	β	n	$\dot{\varepsilon}$ /×10^{-4} h^{-1}
300	0.042302	0.249360	-
500	0.042543	0.250228	–0.47
800	0.042949	0.245450	–0.35
1000	0.043144	0.243371	–0.30

at low and intermediate temperature will appear if creep time is longer enough.

2.4 Creep deformation mechanism

According to the extrapolated minimum creep strain rate, creep stress exponent n is calculated as 6.96，which is close to the former researcher's results[4,5]. The activation energy for the primary creep can be expressed as[22]:

$$Q(\varepsilon) = -R\left[\frac{\Delta \ln \dot{\varepsilon}(\varepsilon)}{\Delta(1/T)}\right]_{\text{const}, \sigma} \quad (9)$$

where R is the ideal gas constant. The curve of $\ln\dot{\varepsilon}$-$1/T$ was plotted as shown in Fig.7, which has a slope that is proportional (by a factor of R) to the activation energy at that particular creep strain. The value of activation energy for deformation of α titanium when slip is the rate-limiting deformation mechanism is given in the range of 30~40 kJ/mol[17, 22], while the activation energy for twin growth is 66 kJ/mol[17,18]. The low temperature primary creep activation energy of TA2 at different strain level is always higher than the activation energy for slip but lower than that for twinning, and thus both slip and twinning are active creep deformation mechanisms for TA2 at low temperature. In order to support the importance of twinning for low temperature creep behavior of TA2, microstructures were investigated by the optical micrograph of specimens.

Based the on metallographic microstructures shown in Fig.8, the density of twinning structure is connected with creep temperature. Song et al.[23] found that as temperature

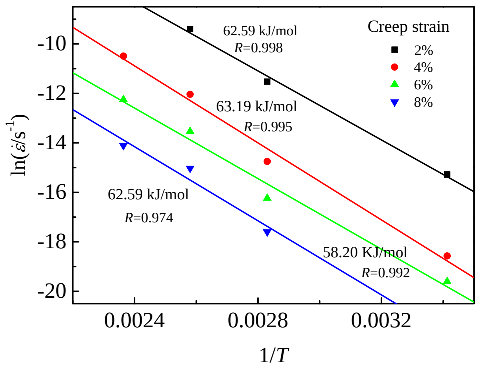

Fig.7 Curves of $\ln\dot{\varepsilon}$-$1/T$

increases, the stress required for the dislocation slip is decreasing and the stress required for twinning remain the same. Thus, as temperature increases, the density of twinning in specimens becomes less and less. At 293 K, many twinning structures as shown in Fig.8a provide sufficient source to activate the long time continuous creep deformation. As the density of twinning decreases with temperature as shown in Fig.8b and Fig.8c, creep behavior of TA2 becomes less and less significant. And this causes the creep saturation at 423 K. At 573 K, twinning structures disappear; thus except the initial load strain, creep strain hardly increases by time as shown in Fig.1f.

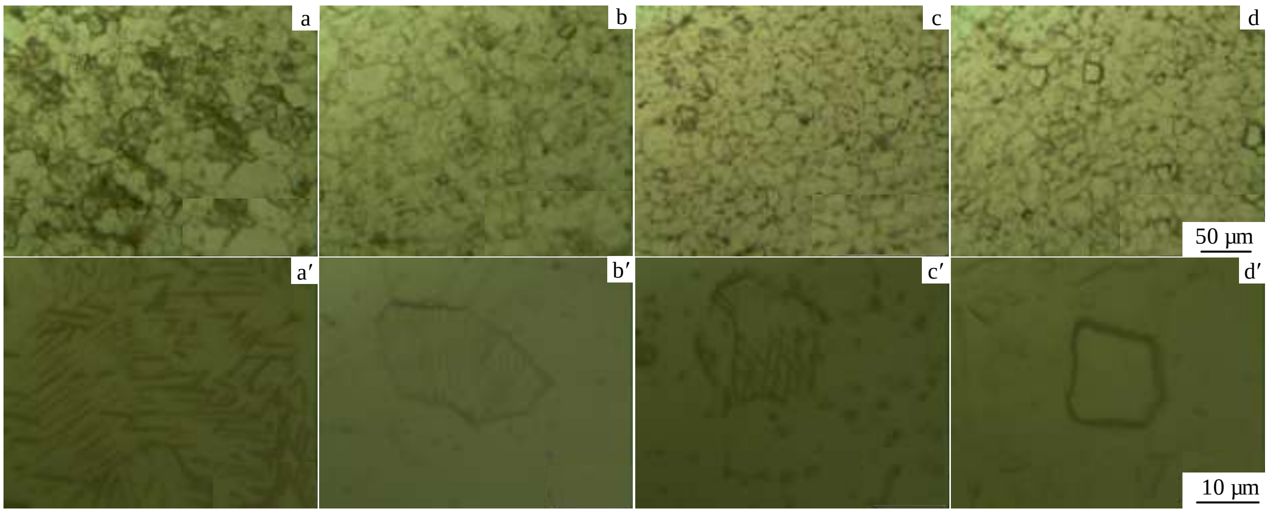

Fig.8 Metallographic microstructures of creep specimens: (a, a′) 293 K, S=1; (b, b′) 353 K, S=1; (c, c′) 423 K, S=1; (d, d′) 573 K, S=1

.3 Conclusions

1) According to the variation of creep strain with applied stress level, the threshold stress of TA2 at low temperature and intermediate temperature is obtained.

2) Based on results of long time creep experiments, the steady state creep at low temperature for TA2 is confirmed.

3) According to the minimum creep rate, stress exponent is calculated as 6.96. Both the activation energy for primary

creep of TA2 and the metallographic images support the importance of twinning for creep of TA2 at low and intermediate temperature.

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工业纯钛 TA2 中低温蠕变特征研究

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摘 要：工业纯钛 TA2 中低温蠕变行为存在显著的温度及应力相关性。基于外加应力水平和蠕变应变的变化关系，确定不同蠕变温度下的门槛应力水平。根据短时蠕变实验数据，利用包含稳态蠕变速率的本构方程外推稳态蠕变速率，而后进行两组相对长时的蠕变实验，证明了工业纯钛中低温蠕变存在稳态蠕变阶段。利用稳态蠕变速率与应力关系，计算出工业纯钛室温蠕变应力指数为 6.96，也说明了外推稳态蠕变速率的可靠性。中低温蠕变激活能随着蠕变进行变化不大（≈60 kJ/mol），但一直大于以位错为变形主导机制的变形激活能（30~40 kJ/mol），表明孪晶对于工业纯钛中低温蠕变发展整个阶段均起重要作用。根据蠕变后试样孪晶结构随温度的变化解释了 TA2 蠕变行为的温度相关性，同时也证明了孪晶对于 TA2 蠕变行为的重要性.

关键词：工业纯钛 TA2；门槛应力；稳态蠕变；蠕变激活能；孪晶

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