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ARTICLE

Stress Relaxation Behavior and Corresponding Constitutive Relation of TA32 Titanium Alloy at High Temperature

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Abstract: Stress relaxation experiments under different combinations of temperatures (775, 800, 825 °C), initial stresses (150, 200 MPa) and pre-strains (7.85%, 15.7%) were performed for TA32 titanium alloy to study the influences of the process parameters on its stress relaxation behavior. The microstructures of the specimen after the experiments at different temperatures were observed to investigate the temperature effects on the microstructure evolution. The stress relaxation curves were fitted with the quadratic delay function. And the creep constitutive equation at the high temperature was established and applied to define the stress relaxation behavior of TA32 titanium alloy in the finite element analysis. The results show that the stress drops rapidly with high stress relaxation rate in the first 200 s of the stress relaxation. The stress tends to be stable and finally reaches the limit of stress relaxation after 3600 s. The stress relaxation rate increases with increasing the temperature while the stress relaxation limit decreases. And the initial stress and pre-strain have little effect on the stress relaxation behavior. The equiaxed and grown grains can enhance the plasticity with the increase of temperature. The simulation results and experimental stress relaxation curves are in good correlation which validates the reliability of the creep constitutive equation.

Key words: TA32 titanium alloy; stress relaxation; constitutive equation

TA32 titanium alloy is a nearly α-type high temperature titanium alloy, developed by Chinese Academy of Sciences replacing Nd of TA12 with Nb and Ta. It has good plasticity and high temperature creep resistance[1]. Therefore, it has good application prospects in aero-engine. However, TA32 titanium alloy is difficult to form at room temperature and has large spring back. Therefore, it is necessary to study hot forming for solving this problem. The stress relaxation and creep behavior of materials at high temperature become the key of research. So, scholars have done a lot of research on the stress relaxation and creep behavior of metal[2].

Based on creep, stress relaxation theory and aging kinetics, Ho et al[3] put forward a set of creep aging constitutive equations for aluminum alloy, and made finite element analysis for the aging forming process of 7010 aluminum alloy panel. Xiao et al[4] studied stress relaxation of TC4 to obtain short-creep constitutive equation of TC4 titanium alloy. Based on classical creep constitutive equation and Garofalo creep constitutive equation, Ma et al[5] established new creep constitutive equation of TB2 titanium alloy under different stress which well predicted the creep behavior of TB2 titanium alloy at 500 °C.

As a new type of titanium alloy, TA32 titanium alloy has been studied less. So, it is of great significance to study its mechanical properties at high temperature for hot forming process. The author of this paper studied stress relaxation behavior of TA32 under different conditions, constructed corresponding stress relaxation equation, derived short-creep constitutive equation at high temperature, and verified the accuracy of constitutive equation to provide theoretical basis for hot forming process of TA32 titanium alloy by simulating process of stress relaxation.

1 Experiment

The experimental material used in this experiment is 1.5 mm thick annealed TA32 titanium alloy plate produced by the limited by Share Ltd of Baoji titanium industry. The chemical composition is shown in Table 1. Standard stress relaxation

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Table 1 Chemical composition of TA32 titanium alloy (wt%)

Al	Sn	Zr	Mo	Si	Nb	Ta	Ti
5.5	3.5	3.0	0.7	0.3	0.4	0.4	Bal.

specimens were prepared according to the national standard GB/T 4338-2006, and the size of specimens is shown in Fig.1. The stress relaxation experiment was carried out on the UTM550X electronic universal testing machine, testing machine was heated to the certain temperature, and after heating for 5 min the experiment started. According to the results of TA32 titanium alloy high temperature tensile test, it is found that the elongation of the material reaches the requirement of TA32 hot forming in the range of 775~825 °C, and the yield strength of the material is above 200 MPa. So experimental temperatures were 775, 800 and 825 °C, the corresponding initial stress were 150 and 200 MPa, the initial strain were 7.85% and 15.7%, and experimental time was 3600 s.

2 Results and Discussion

2.1 Stress relaxation behavior

The stress relaxation curves of TA32 titanium alloy specimens at three different temperatures (initial stress is 150 MPa) are shown in Fig.2. The three stress relaxation curves have the same rules. In the first stage of stress relaxation, the initial stress decreases sharply at the beginning of the experiment; the stress in the second stage of stress relaxation gradually tends to be stable, and finally reaches the limit of stress relaxation.

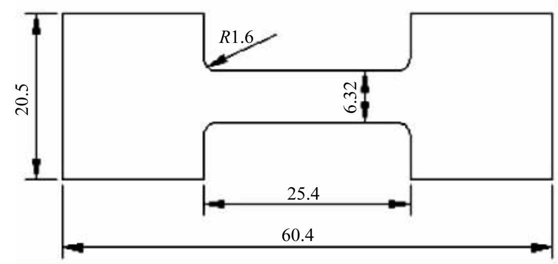

Fig.1 Specimen size of stress relaxation (mm)

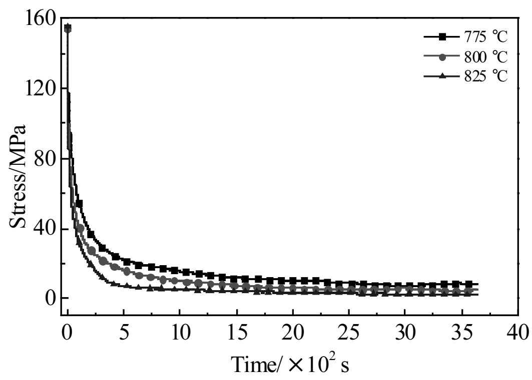

Fig.2 Stress relaxation curves of TA32 titanium alloy

2.2 Effect of technological factors on stress relaxation of TA32 titanium alloy at high temperature

2.2.1 Effect of temperatures on stress relaxation of TA32 titanium alloy sheet

The effect of temperature on stress relaxation can be seen clearly from Fig.2. In the first stage of stress relaxation, the higher the temperature is, the faster the relaxation rate is. In the second stage, the stress relaxation gradually decreases with increasing of temperature. Scholars usually use formula (1) to describe the effect of temperature on stress relaxation[6,7]:

$$d\varepsilon/dt = A\sigma^n \exp[-Q/(RT)] \quad (1)$$

where ε is plastic strain, t is time, A and n are constant, σ is stress, Q is thermal deformation activation energy, R is molar gas constant, and T is temperature. Fig.2 shows that plastic strain rate gradually decreases to a minimum as experiment goes on, and stress relaxation limit decreases with the increase of temperature when combined with Eq.(1).

Fig.3 shows the relation curve between temperature and stress relaxation limit under different initial stress. It can be found that stress relaxation limit of different temperatures is diverse obviously.

2.2.2 Effect of pre-strains on stress relaxation of TA32 titanium alloy sheet

Fig.4 shows the stress relaxation curves under different temperatures and pre-strains. It can be seen that when the temperature is same, the pre-strain is 7.85% and 15.7%, most of the stress relaxation curves are coincident, and the difference of the stress relaxation limit is very small. The results show that the pre-strains have little effect on the stress relaxation behavior of TA32 titanium alloy sheet at high temperature.

2.2.3 Effect of initial stresses on stress relaxation of TA32 titanium alloy sheet

Fig.5 shows stress relaxation curves at different temperatures and initial stresses. As can be seen from Fig.5, when the temperature is the same and the initial stress is 150 and 200 MPa, the corresponding curve finally reaches its stress

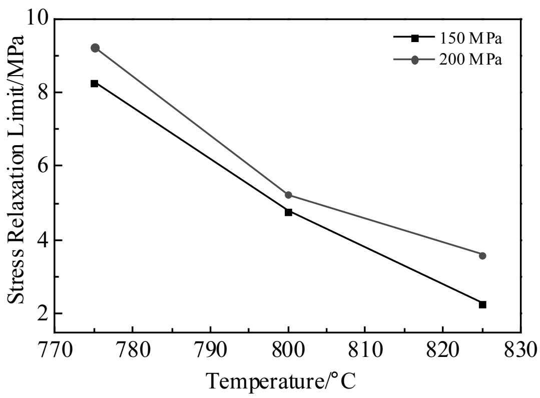

Fig.3 Relationship between stress relaxation limit and temperature

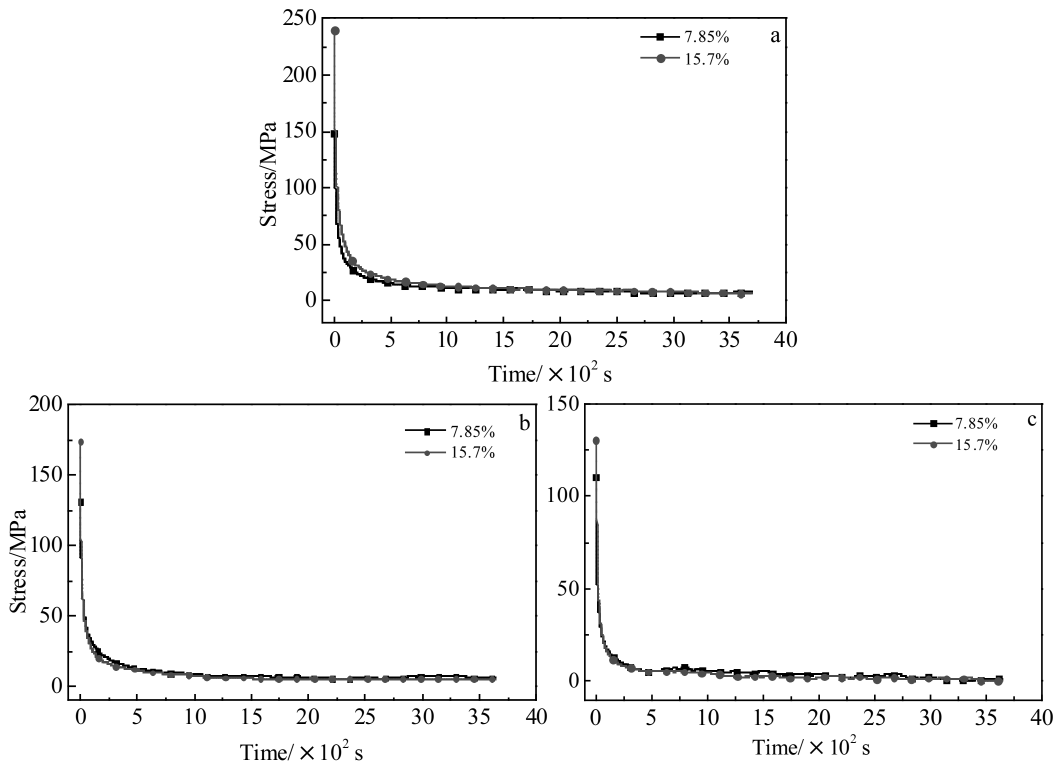

Fig.4 Stress relaxation curves of TA32 alloy at different temperatures and pre-strains: (a) 775 °C, (b) 800 °C, and (c) 825 °C

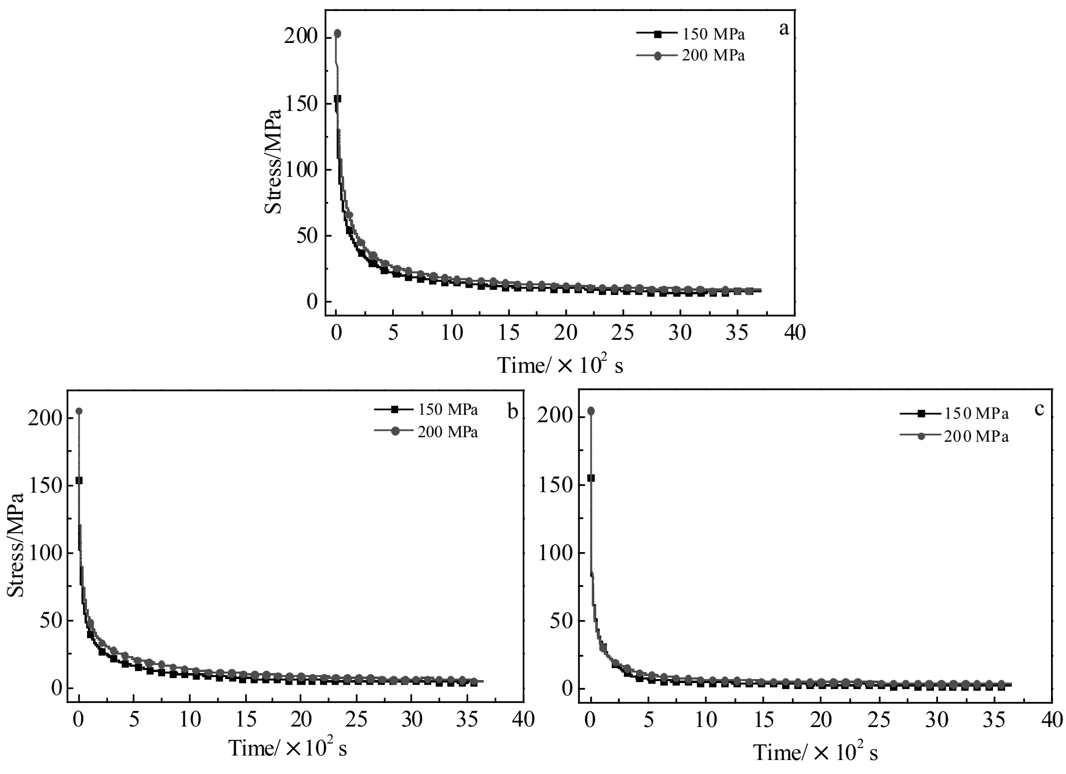

Fig.5 Stress relaxation curves of TA32 alloy at different temperatures and initial stresses: (a) 775 °C, (b) 800 °C, and (c) 825 °C

relaxation limit, and the greater the initial stress, the greater the stress relaxation limit, but the difference between the two is not very large.

2.3 Microstructural observation

Based on the analysis results, temperature has an obvious influence on stress relaxation of TA32 titanium alloy, so the author observed the microstructure of stress relaxation experimental samples at different temperatures. Fig.6 is original microstructures of TA32 titanium alloy and the microstructures of stress relaxation test sample at the same initial stress but different temperatures. The image shows that the microstructure of TA32 titanium alloy consists of matrix α-phase, irregular long strip and equiaxed β-phases. Compared with the room temperature structure, the microstructure of the stress relaxation experiment changes significantly. When the experimental temperature is 775 °C, the long strip grains of the β-phase are transformed into small island grains; when the temperature is 800 °C, there are small β-phase equiaxed grains near the grain boundary of the α-phase which are approximately uniform distribution. The strength of grain and grain boundary in the alloy decreases, so the plastic ability is enhanced. When the temperature is 825 °C, the grains size of the β-phase increases, but eutectoid transformation between the α-phase and the β-phase does not occur obviously. With the increasing of temperature, it can be seen from metallographic structure that the slipping system of TA32 titanium alloy and the microplasticity of the microstructure are enhanced, which is expressed by the fact that the number of stress inducing β-phase to creep gradually increases, so the stress relaxation limit is getting smaller and smaller.

2.4 Fitting of stress relaxation curve

The stress relaxation curves were fitted to get the material instantaneous stress in the stress relaxation process. Scholars usually use empirical formula to fit, such as logarithmic, exponential function and Maxwell equation. The author adopts two delay function in which formula (2) shows to fit[4,8]:

$$\sigma = \sigma_\infty + A\exp(-t/a) + B\exp(-t/b) \quad (2)$$

where σ is instantaneous stress, σ_∞ is stress relaxation limit, t is stress relaxation time, A, B, a and b are undetermined coefficients.

The parameters of stress relaxation equation are shown in Table 2. It can be obtained by fitting the stress relaxation curves under different experimental conditions.

Fig.7 and Fig.8 show the comparison between the fitting equation curve and experimental stress relaxation curve. It is shown that the two-delay function can effectively predict the stress relaxation behavior of TA32 titanium alloy sheet at high temperature.

2.5 Creep constitutive equation

Stress relaxation is that the total strain of material unchanges, and stress decreases gradually with time. The stress relaxation equation can be expressed by formula (3)[9,10]:

$$\varepsilon=\varepsilon_e+\varepsilon_p=\text{constant} \quad (3)$$

where ε is total strain, ε_e is elastic strain, and ε_p is plastic strain. In the process of stress relaxation, the total strain of material remains unchanged, and the elastic strain gradually transforms into plastic strain.

Differentiate the formula (3):

$$d\varepsilon_e/dt+d\varepsilon_p/dt=0 \quad (4)$$

Eq.(4) is changed to get the relationship between the

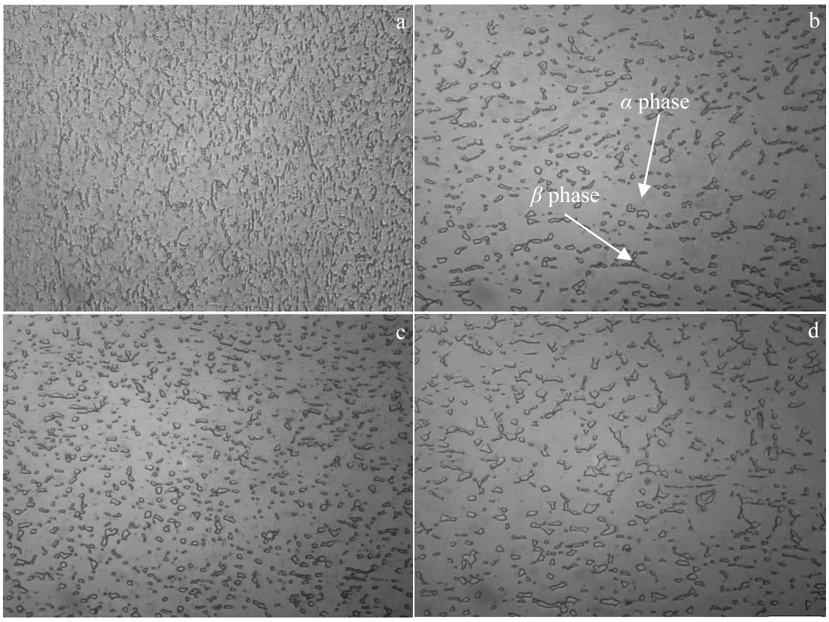

Fig.6 Original microstructure of TA32 titanium alloy (a) and its microstructures at different temperatures (initial stress is 150 MPa): (b) 775 °C, (c) 800 °C, and (d) 825 °C

Table 2 Parameters of stress relaxation equation of TA32 alloy under different conditions

Temperature/°C	Initial state	σ_∞/MPa	A/MPa	B/MPa	a/MPa	b/MPa
775	ε=7.85%	7.823 62	24.652 57	88.553 68	479.145 15	31.145 15
	ε=15.7%	8.458 08	38.637 88	147.120 91	411.867 62	27.342 41
	σ=150 MPa	8.273 66	34.830 25	92.895 23	619.456 3	56.694 9
	σ=200 MPa	10.379 18	114.186 51	43.927 97	114.186 51	575.973 61
800	ε=7.85%	8.655 94	31.048 82	75.192 27	312.292 83	21.315 7
	ε=15.7%	5.630 46	27.303 57	110.734 93	310.103 01	16.936 64
	σ=150 MPa	5.435 43	35.252 46	91.879 11	454.795 52	32.580 88
	σ=200 MPa	7.063 8	114.144 19	39.393 76	32.137 69	555.748 17
825	ε=7.85%	0.003 29	67.598 58	10.269 37	36.232 75	1796.068 3
	ε=15.7%	1.648 13	136.739 46	12.912 95	20.334 9	518.423 33
	σ=150 MPa	3.412 11	79.877 52	51.751 75	15.104 08	179.371 83
	σ=200 MPa	5.061 56	121.751 44	39.637 18	13.918 9	245.873 99

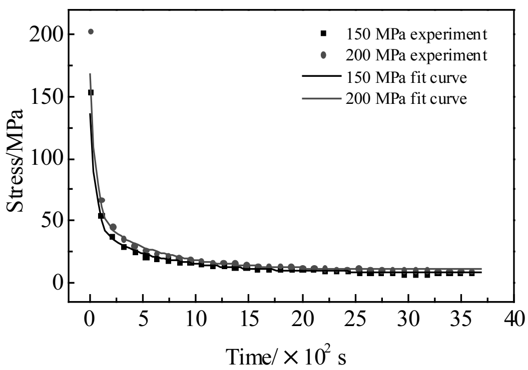

Fig.7 Comparison of experimental and fitting curve at 775 °C and different pre-stresses

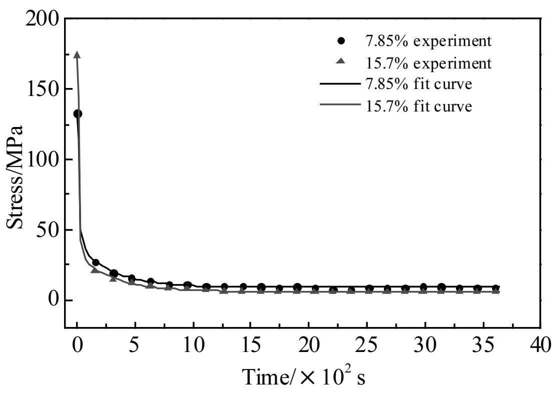

Fig.8 Comparison of experimental and fitting curve at 800 °C and different pre-strains

creep strain rate and the stress[2,8]:

$$\dot{\varepsilon}_{creep}=\mathrm{d}\varepsilon_p/\mathrm{d}t=-\mathrm{d}\varepsilon_e/\mathrm{d}t=-\mathrm{d}\sigma/\mathrm{d}t/E \quad (5)$$

where $\dot{\varepsilon}_{creep}$ is creep strain rate, σ is the stress, and E is modulus of elasticity.

The relationship between the creep rate and the stress can be obtained by using the formula (5) and the experimental data which is shown in Fig.9. It can be seen that the creep rate-stress curves have a non-linear relationship under the same initial stress and different temperature conditions.

The common models used to describe the creep constitutive equation of metal materials are the power exponent function model which is suitable for low stress regions and the hyperbolic sine function model that can predict well the creep behavior of materials under high stress, and automatically degenerate into a power exponential function model under low stress. Therefore, the author uses the hyperbolic sinusoidal function model to establish the creep constitutive equation of TA32 titanium alloy sheet, as shown below[8,11,12]:

$$\dot{\varepsilon}_{creep}=A(\sinh B\sigma)^n \quad (6)$$

where $\dot{\varepsilon}_{creep}$ is creep rate, σ is stress, A, B and n are material parameters.

The relationship between creep rate and stress was fitted to get the material parameters of formula (6) shown in Table 3.

2.6 Simulation of stress relaxation behavior of TA32 titanium alloy

The author simulated the stress relaxation behavior of TA32 titanium alloy (200 MPa, 775, 800, 825 °C) by defining the creep constitutive equation in the finite element analysis. The simulation results and experimental stress relaxation curves are shown in Fig.10. They are basically consistent, and the difference of stress relaxation limit is very small, which validates the reliability of the creep constitutive equation. So, the creep constitutive equation can well predict the stress

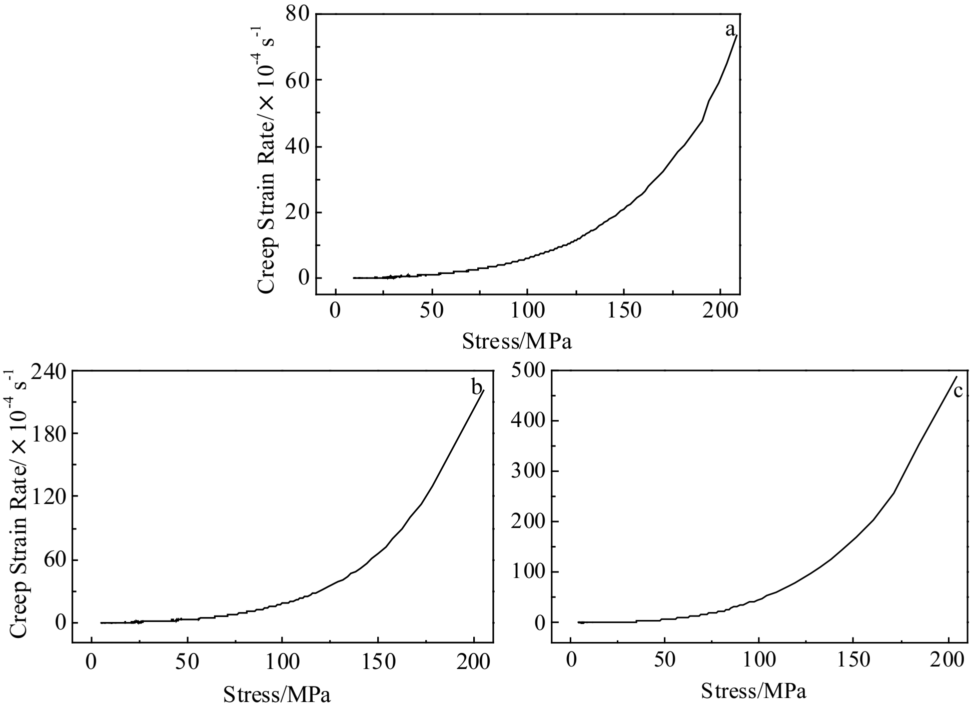

Fig.9 Creep strain rate-stress curves of TA32 alloy at different temperatures: (a) 775 °C, (b) 800 °C, and (c) 825 °C

Table 3 Parameters of creep constitutive equation at high temperature

Temperature/°C	A/MPa^{-1}·s^{-1}	B	n	Initial stress/MPa
775	6.541 58×10^{-4}	0.008 58	2.265 11	200
800	0.002 2	0.008 16	2.505 1	200
825	0.009 96	0.006 85	2.562 97	200

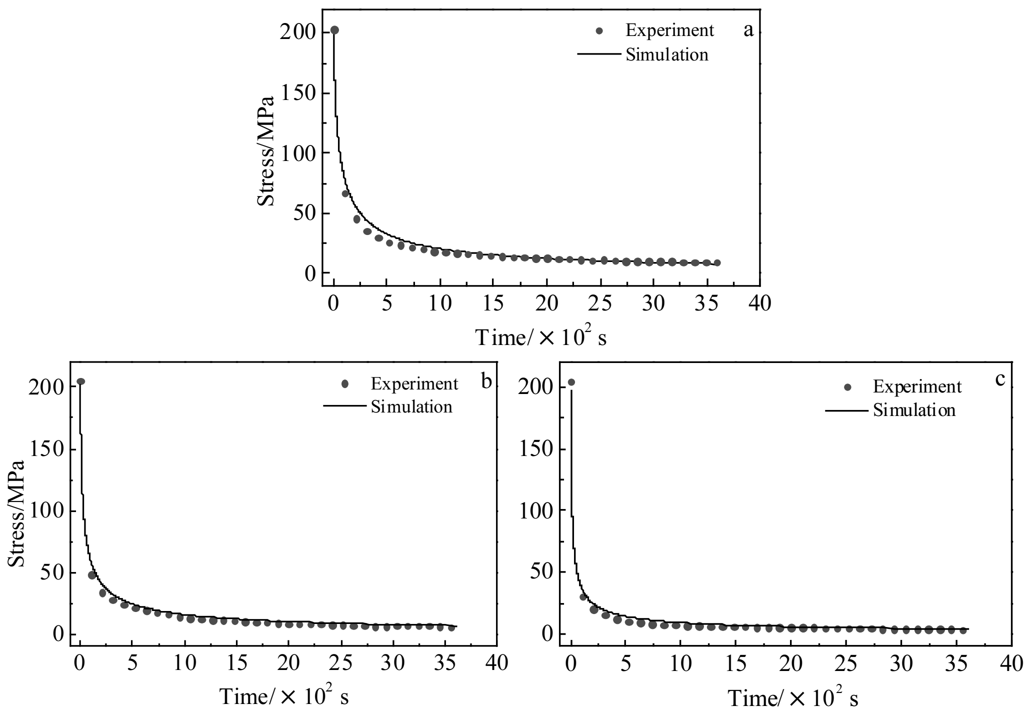

Fig.10 Comparison of simulated results and experiment curves at different temperatures: (a) 775 °C, (b) 800 °C, and (c) 825 °C

relaxation behavior of TA32 alloy at high temperature above 775 °C[13,14].

3 Conclusions

1) The effect of temperature on stress relaxation of TA32 titanium alloy is obvious. The higher the temperature is, the greater the stress relaxation rate is, and the smaller the stress relaxation limit is. The pre-strain and initial stress have little effect on the stress relaxation behavior.

2) The equiaxed and grown β-phase grains can enhance the plasticity with the increase of experimental temperature.

3) The stress relaxation curves of TA32 titanium alloy can be fitted by two-delay function in the range of 775 °C to 825 °C.

4) The relationship between creep strain rate and stress can be deduced through the material stress relaxation equation to establish the creep constitutive equation of TA32 titanium alloy at different temperatures.

5) The simulation results and experimental stress relaxation curves are in good correlation which shows that creep constitutive equation can be used to describe the stress relaxation behavior of TA32 at high temperature.

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TA32 钛合金高温应力松弛行为及其对应的本构方程

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摘　要：在不同温度（775、800、825 ℃）、不同初应力（150、200 MPa）和不同预应变（7.85%、15.7%）下进行 TA32 钛合金高温应力松弛实验，研究了工艺参数对应力松弛行为的影响。对实验后的试样进行微观组织观察，分析了温度对微观组织的影响。利用二次延迟函数对应力松弛曲线进行拟合，推导得到高温蠕变本构方程，进而将其应用于 TA32 钛合金应力松弛行为有限元模拟。结果表明：在应力松弛的前 200 s，应力松弛速率很快，其应力急剧下降，经过 3600 s 后应力逐渐趋于平缓并最终达到松弛极限。应力松弛行为随着温度的升高而加快，但其松弛极限随之减小，初应力和预应变则对其影响不大。随着温度的升高晶粒发生了等轴化和长大现象，塑性增强。模拟结果和应力松弛的实验曲线有较高的吻合度，验证了此蠕变方程的可靠性。

关键词：TA32 钛合金；应力松弛；本构方程

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