Effect of pre-strain on creep behaviour and constitutive
modelling of titanium alloy sheets

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Abstract. This paper discusses the effect of pre-strain on the creep behaviour and constitutive modelling of titanium alloy Ti-3Al-5Mo-5V-8Cr sheets. A set of uniaxial tensile creep tests at different pre-strains and different stresses were carried out to analyse the creep behaviour of titanium alloy sheets. The results show that pre-strains have significant influence on the creep behaviour which was opposite to the effect of stress. And based on the experiment results, a modified Garofalo creep constitutive model was established which can illustrate the creep aging behaviour of titanium alloy Ti-3Al-5Mo-5V-8Cr sheet at 500°C under different stresses and different pre-strains very well.

1. Introductions
Titanium alloys based on the β phase are attractive materials for their high strength (in the range of 700-1000MPa), relatively low density (lie between steel and aluminum alloys), good ductility, as well as good fracture toughness and corrosion resistance [1, 2]. A good example is Ti-3Al-5Mo-5V-8Cr, which has been used in a number of high performance aerospace applications due to its good cold working formability, significant heat-treatment strengthening, satisfactory welding performance and so on [3]. Generally, for parts that contain complicated structures, the forming process include cold preforming and then hot sizing, also known as creep age forming (CAF), so as to eliminate size error, shape distortion and residual stress. However, the process of cold preforming may introduce pre-strain condition, which may influence the creep aging behaviour. In order to acquire high precision description of such process applied with titanium alloys, it is necessary to investigate the effect of pre-strain on creep aging behaviour for their CAF applications.

Due to the length limitation of the paper, we will briefly summarize the research work for the effect of pre-strain on the creep behaviour. According to relevant researches, pre-strain before aging process can increase the dislocation density in the alloy, reduce the size of precipitates and shorten the time for the peak-aged [4, 5]. Meng W. has found that the creep strain of Al-Li-S4 alloy sample without pre-strain is greater than that of the ones with pre-strains, which can also acquire that the steady state strain rate of sample without pre-strain is larger than the ones with pre-strains. However, the law in different pre-strain samples is different, with the larger pre-strain, the creep strain and the steady creep strain rate are larger [4]. Xu y. has observed that the creep strain and creep strain rate of the pre-strain samples are distinctly greater than that of un-strained sample, and the same phenomenon occurred in different pre-
strains [5]. Compare to the research of pre-strain effect in aluminum alloys, limited effort has been made to test the pre-strain effect on creep aging behaviour of titanium alloys.

The objective of the present paper is to investigate and incorporate the effect of pre-strain on the creep behaviour and the creep constitutive modelling of titanium alloy Ti-3Al-5Mo-5V-8Cr sheets. Various pre-strains (0%, 1%, 3%, and 5%) of Ti-3Al-5Mo-5V-8Cr have been experimentally investigated by creep aging tests under different stresses. And then the effect of pre-strain on the creep aging behaviour has been analyzed. Finally, based on the analysis and experimental data, a creep constitutive model considered the effect of pre-strain was established by modifying Garofalo’s equation. And this work could provide certain support for the manufacturing of aerospace parts which contain pre-strain after cold preforming and the development of CAF technology about metastable β titanium alloys.

2. Experimental method

2.1. Test material
The material used in this research was metastable β titanium alloys Ti-3Al-5Mo-5V-8Cr. The as-received material was a 1.8mm thick sheet, which was supplied in the form of hot-rolled and solution-treated at 800°C, air-cooled to room temperature.

2.2. Uniaxial creep tensile tests
According to the creep aging process recommended by Leyens C and Peters. M[6], which noted that the appropriate creep aging temperature for Ti-3Al-5Mo-5V-8Cr is 450°C–550°C and the time is 8–24 hours. So in this research, we focus on the creep aging behaviour of Ti-3Al-5Mo-5V-8Cr in 12 hours and at temperature of 500°C.

The preparation of pre-strained creep test specimens were carried out on Zwick Roell tensile test machine at room temperature with static deformation condition. Pre-strain values of 1%, 3% and 5% were chosen based on the deformation after cold working process at room temperature.

The mechanical property of Ti-3Al-5Mo-5V-8Cr at 500°C was tested on Zwick Roell machine too. As shown in table 1, the yield strength of as-received material at 500°C was about 520MPa. So in this study, constant stress value of 156MPa, 208MPa and 260MPa, which also calculate as 0.3σ500°C, 0.4σ500°C and 0.5σ500°C respectively, were chosen to study the creep behaviour of specimen without pre-strain. For the purpose of comparision, the stress of 260MPa was chosen for different pre-strains. Uniaxial tensile creep tests were carried out at 500°C using RDL50 constant-stress creep test machine.

| Temperature | Elastic Modulus | Yield strength | Tensile strength | Ductility |
|-------------|----------------|----------------|-----------------|-----------|
| 500°C       | 52.7GPa        | 520.82MPa      | 581.7MPa        | 69.9%     |

3. Results and discussion
Typical creep curves of different constant stresses and different pre-strains at 500°C and 12 hours are given in Figure 1 (a) and Figure 1 (b). It can be seen clearly that Ti-3Al-5Mo-5V-8Cr exhibits typical features of the primary and secondary creep stages. As illustrated in Figure 1 (a) and Figure 1 (b), the effect of pre-strain on the behaviour of creep strain is significant just like the effect of constant stress.
From figure 1(b), with the increase of pre-strain, the creep strain decrease obviously. And compared with the one without pre-strain, it indicated that all of the pre-strains cannot improve the formability of Ti-3Al-5Mo-5V-8Cr in creep aging forming process, which is opposite to the phenomenon during creep aging of AA2524 founded by Xu [4]. Also, this creep aging behaviour is contrast with the results founded by Wang [5], which come to a conclusion for Al-Li-S4 alloys that the larger the amount of pre-strain is, the larger of the total creep strain. These differences may be explained by the creep mechanism and the aging precipitation are different with different materials. As for Ti-3Al-5Mo-5V-8Cr, one possible explanation is that a large number of defects like dislocations were produced due to pre-strain before creep, which yielded more nucleation sites and enhanced β/α phase transformation. And this results in more obstacles for dislocation motions during creep process.

4. Creep constitutive model coupled with pre-strain

In the terms of theoretical development, there are many researches devoted to the development of creep aging forming models based on macroscopic approach and micromechanics approach. For convenience in engineering application, the present paper is constructed in the realm of a macroscopic approach and follows a classic model, originally proposed by Garofalo [7], which was defined as:

$$\varepsilon_{\text{creep}} = \varepsilon_0 + \varepsilon_T (1 - e^{-rt}) + \dot{\varepsilon}_s \dot{t}$$

(1)

Where $\varepsilon_0$ refers to the instantaneous strain on loading, $\varepsilon_T$ corresponds to the asymptotic transient strain component, parameter $r$ is a time constant relating to the rate of exhaustion of primary creep and $\dot{\varepsilon}_s$ is the steady creep rate.

Based on the creep constitutive model equation (1), this paper has come up with a modified creep constitutive model coupled with the effects of pre-strain and stress, which can be described as follows:

$$\begin{align*}
\varepsilon_i &= \varepsilon_T (1 - e^{-rt}) + \dot{\varepsilon}_i \dot{t} \\
\varepsilon_T &= (\alpha + \beta e^{-\gamma \sigma_m})\sigma^m \\
\dot{\varepsilon}_i &= k\sigma^n
\end{align*}$$

(2)

Where $\varepsilon_{pre}$ and $\sigma$ represent the pre-strain and stress, respectively. And $r, \alpha, \beta, \gamma, k, m, n$ are material constants.

With above creep experiment data, an advanced optimization algorithm, i.e., Genetic Algorithm, is employed by MATLAB to get accurate constants as listed in Table 2. And figure 2 shows the comparison between calculated and experiment data. It can be seen that the modified model couple with effects of pre-strain and stress can illustrate the creep aging behaviour of Ti-3Al-5Mo-5V-8Cr alloy under different stresses and pre-strains very well.
Table 2. Modified constitutive model parameters for Ti-3Al-5Mo-5V-8Cr at 500°C.

| Parameters | r   | α   | β   | γ   | k   | m   | n   |
|------------|-----|-----|-----|-----|-----|-----|-----|
| Values     | 1.26e-4 | 7.43e-6 | 12.57e-6 | 45.65 | 7.2e-11 | 1.56 | 1.72 |

Figure 2. Comparison of experimental and computed creep curves at 500°C (a) different stresses (b) different pre-strains.

5. Conclusions
The effect of pre-strain on the behaviour of creep strain is significant just like the effect of stress and the existence of pre-strain deteriorates the formability of Ti-3Al-5Mo-5V-8Cr alloy in creep aging forming process. With the experiment data, a modified creep aging constitutive model which can reflect the influence of both different stresses and pre-strains has been established. And it can illustrate the creep aging behaviour of Ti-3Al-5Mo-5V-8Cr alloy sheet at 500°C under different stresses and pre-strains very well.

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