Study on the Transient Creep Stage by Small Beam Specimen with Fixed Constraints

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Abstract. Three-point bending specimen with fixed constraint (TPBSF) has potential advantages in engineering application because of its simple stress state and easily achievement of rupture data. It is critical to accurately evaluate the creep curve of TPBSF for the application in engineering. In this study, TPBSF behavior of aluminium alloy A7N01 at 653K has been investigated at various loads in the range 12-20N. The creep curve clearly exhibited transient, steady-state and tertiary stages. The creep displacement data has been analysed according to the Garofalo’s equation. The rate of exhaustion of transient creep exhibited similarly dependence on load as steady-state displacement rate. It indicates that the transient and steady-state creep displacement of TPBSF obey the same kinetics law. The time to attain the steady-state stage and the rupture time are approximately inversely proportional to the rate of exhaustion of transient creep. The transient stage of TPBSF creep accounts for about 34% of the overall creep time. It is useful for predicting TPBSF creep deformation and residual life of the material.

1. Introduction

Creep properties are generally determined by using standard tensile creep testing, which requires sufficient material provision to manufacture specimens. However, the large-volume specimens may cause damage to in-service components. For some special structures, such as thin-plate structures, it may be impossible to provide enough material for standard tensile specimens [1]. Small specimen creep testing technique has therefore been developed. Among them, the three-point bending specimen with fixed constraint (TPBSF) has been attracting much attention due to its simple stress state and easily achievement of rupture data.

Many studies have been done to develop the TPBSF testing techniques. Xu et al [2] measured creep behaviour of materials by bending tests. Wen et al [3] carried out bending tests to measure the creep damage of materials. Zhuang et al [4] deduced the creep deformation constitutive of TPBSF based on beam bending theory. Bai et al [5] revised the creep deformation constitutive of TPBSF by introducing coefficient $\lambda$. Qin et al [6] established formulas of equivalent strain and stress of TPBSF in the large deformation stage. It is generally observed that creep deformation constitutive equations has been largely studied in the literature, with less emphasis on the TPBSF curve. It is therefore essential to give attention on the deformation of TPBSF in the detail.

In this study, TPBSF behavior of aluminium alloy A7N01 has been evaluated under various loads in the range 12-20N and at temperature 653 K with a temperature accuracy of ±1K. The transient creep displacement data have been analysed according to the Garofalo’s equation. Then the
relationships among the rate of exhaustion of transient creep ($\kappa$), steady-state displacement rate ($\dot{d}_s$), the time to attain the steady-state stage ($t_s$), rupture time ($t_r$) has been studied.

2. Theoretical Analysis of Transient Creep Displacement
Webster [7] proposed the concept of transient creep as a first-order process that is the change of creep rate in transient and steady-state regions can be described by the first-order reaction kinetics as follow,

$$\frac{d(\dot{\varepsilon} - \dot{\varepsilon}_s)}{dt} = -\frac{\dot{\varepsilon} - \dot{\varepsilon}_s}{\tau}$$

(1)

Where $\dot{\varepsilon}$ is the creep rate in transient, $\dot{\varepsilon}_s$ is the steady-state creep rate, $\tau$ is the relaxation time for rearrangement of dislocations.

According to equation (1), the rate of change of creep rate is proportional to the creep rate. The strain-time relation including transient creep and steady-state creep can be obtained by integrating equation (1) twice,

$$\varepsilon = \varepsilon_0 + \varepsilon_1 (1 - e^{-\tau t}) + \dot{\varepsilon}_s t$$

(2)

Where $\varepsilon_0$ is instantaneous strain, $\varepsilon_1$ is limiting transient creep strain, and $r = 1/\tau$ is the rate of exhaustion of transient creep.

Equation (2) has confirmed by Garafalo [8]. According to the equation (2), the total transient creep strain is finite. Initial creep rates that is transient creep rates at $t = 0$ are finite and equal to $\dot{\varepsilon}_t r + \dot{\varepsilon}_1$. A similar expression to equation (2) has been proposed for TPBSF displacement ($d$) as [9],

$$d = d_0 + d_1 (1 - e^{-\kappa t}) + \dot{d}_s t$$

(3)

Where $d_0$ is the instantaneous displacement at $t = 0$, $d_1$ is limiting transient creep displacement, $\kappa$ is the rate of exhaustion of transient creep and $\dot{d}_s$ is steady-state displacement rate.

The rate of exhaustion of transient creep $\kappa$ can be obtained by rearranging equation (3). The expression for $\kappa$ is,

$$\kappa = -\frac{1}{t} \cdot \ln \left( 1 - \frac{\Delta}{d_s} \right)$$

(4)

Where $\Delta = d - d_0 - \dot{d}_s \cdot t$ is the component which becomes zero at $t = 0$ and closer to $d_s$ at the time to attain steady-state stage.

3. Experimental
The aluminium alloy A7N01 was selected in the test, which was the type with the highest strength at room temperature. The chemical composition is shown in table 1.

| Table 1. Chemical composition of A7N01 (wt%) |
|---------------------------------------------|
| Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | Zr  | Al  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.25| 0.25| 0.20| 0.15-0.40| 1.10-1.70| 0.05-0.15| 4.40-5.00| 0.02-0.06| 0.10-0.25| Bal. |

The sample section is rectangular and the size is shown in figure 1. The specimen was held between upper and lower dies. Constant load was applied at the central part of specimen by an indenter with a semi-cylindrical surface of radius $r = 1$ mm. The total length of sample $L = 20$ mm, the width $b = 1.9$ mm, the thickness $2h = 1$ mm, the span $l = 12$ mm. TPBSF tests were carried out on
aluminium alloy A7N01 at various loads in the range 12-20N and at temperature 653K with a temperature accuracy of ±1K [4]. In order to estimate the dispersion of the test, TPBSF tests were carried out on three groups at a load of 14N at 653K. The displacement curve of load point was shown in figure 3. The displacement curves obtained from three tests are basically coincide. The maximum scatters of rupture time among these tests are 16.4%. According to the requirements in the literature [10], the dispersion of 16.4% is completely acceptable for creep tests.

4. Results and Discussion

4.1. TPBSF Curves

Figure 3 shows the typical TPBSF curves obtained from aluminium alloy A7N01 at 653 K at various loads. The displacement-time curves of TPBSF is similar to that of uniaxial creep test, which can be divided into the transient stage, the steady-state stage and the tertiary stage. However, the deformation of TPBSF includes the initial instantaneous bending deformation and the creep deformation. The load-point creep deformation obtained by subtracting the instantaneous deformation from the total deformation values. It can be calculated by the equation (5).

\[ d_c = d - d_0 \]  \hspace{1cm} (5)

Where \( d_c \) is the creep displacement, \( d \) is the total displacement, \( d_0 \) is the instantaneous displacement.

In order to compare the effects of different applied loads on the steady-state displacement rate. The displacement rate curves that were determined by differentiating displacement-time curves are plotted against normalized time \( t/t_r \), as show in figure 4. Where \( t \) is the creep time and \( t_r \) is the rupture time.

It is observed that with the increase of applied loads, the steady-state displacement rate increases.
4.2. Transient Creep Behavior

Figure 5 shows the division of the different creep stages of TPBSF curve. It is observed that the initial displacement $d_0$ is not equal to zero because of applied load. The slope of the fitting line of the steady-state creep stage is taken as steady-state displacement rate $\dot{d}_s$, and its intercept subtract initial displacement is transient displacement $d_T$.

According to the equation (4), $\kappa$ reveals the continuous state of the transient creep. The value of $\kappa$ is calculated as the slope of $\ln(1-\Delta/d_T)$ versus $t$ plot at each applied load. The rate of exhaustion of transient creep $\kappa$ versus applied load in the log-log coordinate system is plotted in figure 6. The relationship between the steady-state displacement rate and the applied load is also shown in the same figure. As is shown in the figure 6, the steady-state displacement rate has a power-law relationship with applied load, which conforms to the constitutive equation of TPBSF in the literature [9]. The rate of exhaustion of transient creep exhibited a similar kind of dependence on load as that of steady-state displacement rate.

The relationship between the rate of exhaustion of transient creep and the steady-state displacement rate is shown in the figure 7. It is observed that the rate of exhaustion of transient creep and the steady-state displacement rate are almost linearly related. The relationship is found as equation (6). It indicates that the transient stage and steady-state stage of creep obey the same kinetics law.

$$\kappa = 4.6d_s^{0.91}$$

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Figure 8. Relationship between the rate of exhaustion of transient creep and the time attain the steady-state stage.

Figure 9. Relationship between the rate of exhaustion of transient creep and the rupture time.

The rate of exhaustion of transient creep $\kappa$ can only reveal the state of the transient stage of creep. The validity of $\kappa$ ends when the time attain the steady-state stage. According to the equation (4), it can be found that as time approaches steady-state, $1 - \Delta/d_t$ is going to approach zero. Therefore, the moment when $1 - \Delta/d_t = 0.01$ is defined as the time to attain steady-state stage ($t_s$). The relationship between $\kappa$ and $t_s$ is shown in the figure 8. It is observed that the relationship between $\kappa$ and $t_s$ is almost inversely proportional. The relationship is obtained as equation (7). It is very convenient to predict the time to attain steady-state stage by the value of $\kappa$.

$$\kappa = 3.74t_s^{-0.997}$$

The relationship between the rate of exhaustion of transient creep and the rupture time is shown in the figure 9. The rate of exhaustion of transient creep is almost inversely proportional to the rupture time ($f_t$), as the relationship between $\kappa$ and $t_s$. The relationship is obtained as equation (8),

$$\kappa = 10.96t_t^{-0.993}$$

The relationship between the time to attain steady-state stage ($t_s$) and the rupture time ($f_t$) can be obtained by comparing equation (7) and equation (8) as,

$$\frac{t_s^{0.997}}{f_t^{0.993}} = 0.341$$

It can be approximately written as,

$$\frac{t_s}{f_t} = 0.341$$

The time to attain steady-state stage ($t_s$) reveals the duration of the transient stage of creep. The rupture time ($f_t$) represents the total creep time. According to equation (10), the transient stage of TPBSF creep test of A7N01 at temperature 653K accounts for about 34% of the overall creep time. The ratio of $t_s$ to $f_t$ under different applied loads is compared with the predictive value, as shown in table 2. It can be observed that the error between the actual value and the predicted value of $t_s/f_t$ is small under each load. It indicates that equation (7) and equation (8) are of high accuracy. However, the applicability of equation (10), that is, whether the transient stage accounts for 34% or about 34% of the total creep time for all TPBSF creep curves, remains to be verified.
Table 2. The error of $t_s/t_f$ between the actual value and the predicted value under different loads

| Load $P$ (N) | 12  | 14  | 16  | 18  | 20  |
|-------------|-----|-----|-----|-----|-----|
| $t_s/t_f$   | 0.32| 0.341| 0.368| 0.345| 0.304|
| Predictive value |     | 0.341|     |     |     |
| Error (%)  | -6.16| 0   | 7.92| 1.17| -10.85|

5. Conclusion

In this study, three-point bending specimen with fixed constraint (TPBSF) behavior of aluminium alloy A7N01 has been investigated at various loads in the range 12-20N and at temperature 653 K. The creep displacement data obtained from the test are analysed according to the Garofalo’s equation. The following conclusions have been drawn from the study.

1) The displacement-time curves of TPBSF is similar to that of uniaxial creep test. The creep curve clearly exhibited transient, steady-state and tertiary stages. The steady-state displacement rate is positively correlated with the applied load, while the rupture time is negatively correlated with the applied load.

2) The trend of variations of rate of exhaustion of transient creep displacement and steady-state displacement rate with applied load indicates that the transient and steady-state creep displacement of TPBSF obey the same kinetics law.

3) The rate of exhaustion of transient creep is almost inversely proportional to the time to attain steady-state stage and the rupture time. The transient stage of TPBSF creep accounts for about 34% of the overall creep time. But the applicability remains to be verified.

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7. References

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