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# Relationship between constant-load creep, decreasing-load creep and stress relaxation of titanium alloy

Po Liu, Yingying Zong*, Debin Shan, Bin Guo**

*National Key Laboratory for Precision Hot Processing of Metals & School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, PR China*

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ABSTRACT

The mechanism of sheet metal parts hot sizing is considered as constant-strain stress relaxation due to creep. This creep deformation in stress relaxation is limited within the elastic strain range, unlike multi-step decreasing-load creep test in which the creep deformation is unlimited. In this paper, the short-term constant-load, decreasing-load creep and stress relaxation tests were performed on Ti6Al4V alloy specimens at 700 °C. The initial stress in the range of 5–126 MPa was applied in constant-load and decreasing-load creep, and initial strain of 0.002, 0.004, 0.0065 and 0.02 was loaded during stress relaxation. The two kinds of creep tests were performed for 3600 s while stress relaxation tests for 1800 s. The creep rate–stress, creep rate–time and creep strain–time relationships were studied respectively based on the test data. Constitutive creep models were developed according to constant-load creep and stress relaxation data, respectively. Application of the established models on simulation of constant-strain, constant-load and decreasing-load creep was introduced. Results show that the creep model from the SRT test is able to predict the stress relaxation behavior well while creep model from the constant-load creep tests is reliable in the simulation of constant-load and decreasing-load creep deformation.



## 1. Introduction

Thermal creep forming (also called multistage forming) is a key manufacturing technique for titanium alloy sheet metal parts. By utilizing this method, many titanium alloy components have been manufactured, such as skin and thin-walled structures [1–4]. Those metal parts are able to satisfy the aerospace industry requirement, which is ascribed to that springback is greatly reduced in hot sizing stage following the sheet forming. In this short sizing stage (usually 5–30 min), the deformed-part shape is held firmly against the tool and the internal stress is thus allowed to relax. The decrease in stress with time is due to transformation from elastic strain to plastic strain, namely creep. Here, the driving force for the creep is considered to be the ever-decreasing stress of material during stress relaxation (SRT). As the internal stress decreases, the creep strain increase tendency becomes more and more slowly. The decrease in elastic strain in turn results in reduction of stress. Therefore, creep and stress relaxation occur simultaneously, and they influence each other.

Since the total strain is kept constant during stress-relaxation, the creep in SRT test is also called constant-strain (C-S) creep, according to the work by Sinha [5]. Here, the C-S creep resembles multi-step decreasing-load (D-L) creep deforming, in which the applied load gradually decreases with time. The difference is that the total strain is kept constant in C-S creep while the D-L creep strain is unlimited. The constant-load (C-L) creep and C-S creep were found to be complementary, as summarized by Chandler [6]. It was found that shear strain rate, obtained from C-L creep and C-S creep (SRT) tests conducted on copper [6], showed linearity with the normalized stress. The stress–strain rate relationship obtained from SRT test on Al–Mg alloys was consistent with that of C-L creep, found by Li et al. [7]. Based on SRT data, the pseudo-tensile and creep strain–time curves were constructed by Woodford et al. [8]. Similarly, a SRT damage model was established in accordance with C-L creep data by Guo et al. [9] to predict relaxation damage life of bolting material 1Cr10NiMoW2VNbN. Thus, according to the two kinds of tests, results from one can be used to calculate behavior in the other. However, the researches [6–9] above are mostly performed aimed at high-temperature property or life-evaluation at service temperature, while few were on hot sizing of titanium alloy.

As for small creep deformation, creep strain (smaller than limiting elastic strain), accumulated in 10 min during C-S creep

* Corresponding author. Tel./fax: +86 451 86418640.
** Corresponding author. Tel./fax: +86 451 86418183.
*E-mail addresses:* hagongda@hit.edu.cn (Y. Zong), guobin@hit.edu.cn (B. Guo).

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tests on Ti-6246 alloy, increased with elastic pre-strain increasing, as summarized by Sinha and Sinha [10]. At the same temperature, similar creep strain was also achieved in 30–50 min in C-L creep tests under 300 MPa on the same material, according to the work by Sinha [5]. This implies that the deformations in C-S creep and C-L creep tests are comparable at specified condition, and certain relationship could exist between them. In addition, the C-S creep can be deemed as kind of creep under step-by-step decreasing load. Maldini and Lupinc found that creep proceeded first at primary creep rate under each stress level in the one-step decreasing load creep test [11]. This is different with the view that creep rate at each instantaneous stress during C-S creep is linked to the minimum rate [10]. Overall, it reveals that connection could be established among C-L, D-L and C-S creep in terms of strain–time, as well as creep rate–stress. Nevertheless, so far such connection lacks of systematic research.

In this paper, short-term C-L and D-L creep tests, as well as C-S stress relaxation tests, are performed on Ti6Al4V alloy at 700 °C. First, three types of creep test data are analyzed. Secondly, the relationship between creep rate and stress, as well as creep rate–time and creep strain–time, is respectively explored based on the obtained creep data. After that, the constitutive creep models are built according to C-L and C-S creep data. Finally, the application of the established models on the finite element simulation in these three kinds of creep forming is introduced and effects of the constitutive models on creep forming simulation accuracy are compared.

## 2. Experimental procedures

Material used in this work was 0.8 mm thick sheet of Ti6Al4V alloy, and its chemical composition (in wt%) is 5.79Al–3.86V–0.07Fe–0.15Si–0.03C–0.12O–Ti. The as-received material is equiaxed by hot rolling and following annealing for 40 min at 800 °C. The white β phase is present in the α grain boundaries, as shown in Fig. 1. The average grain size of α is 2.98 μm. The dimensions of specimens are 15 mm in width, 0.8 mm in thickness, 100 mm in gauge length and 235 mm in total length. All kinds of tests were carried out on an electronic creep testing machine. Specimen elongation measurement was performed by an extensometer with an accuracy of 0.5% and the load was recorded by a load cell with capacity of 50 kN. The initial gauge length of the extensometer was 100 mm, equal to the gauge length of the specimen and its full measurement scale is about 36 mm. The closed-loop controlled system was used to provide constant load in C-L creep tests, as well as inconstant load in D-L and C-S creep tests, by pulling the hole in the clamped ends of the specimen with pin bolts. The isothermal environment was provided by a three-zone furnace with accuracy of ±1 °C. The output power of the furnace was set as 30 kW, therefore it took 100 min to heat up to 700 °C and another 10 min for temperature uniformity. In each test, three thermocouples were attached to the top, middle and bottom section of specimen surface for better maintaining homogenous temperature. In this paper, all kinds of tests were performed at 700 °C. In C-L creep tests, constant load of 216, 540, 972 and 1512 N, corresponding to the initial stresses of 18, 45, 81 and 126 MPa, were applied, respectively. In D-L creep, several steps of changing load were applied in the purpose of better imitating the way of stress relaxation, according to the load switching procedure shown in Table 1. For all C-L and D-L creep tests, the same loading and unloading velocities of 2.5 kN/min were applied. The C-L and D-L creep time of 3600 s was adopted since titanium alloy parts hot-sizing time is short. In stress relaxation (C-S creep) tests, the pre-strain was loaded respectively to 0.002, 0.004, 0.0065 and 0.02 at strain rate of 0.0005 $s^{-1}$. And then, the stress was allowed to relax for 1800 s. Moreover, stress relaxation time of 0, 45, 180 and 600 s was adopted respectively with the fixed pre-strain of 0.02. Here, the SRT time of 0 s means immediately unloading as soon as the strain of 0.02 was achieved. After each SRT time was reached in C-S creep tests, the specimen was released by reducing the load to zero. Simultaneously, in order to calculate the C-S creep strain in each SRT time, elongation change of the specimen due to elastic recovery was continuously recorded for 10 min. All specimens were cooled to 300 °C inside the furnace after testing and then taken outside for air cooling.

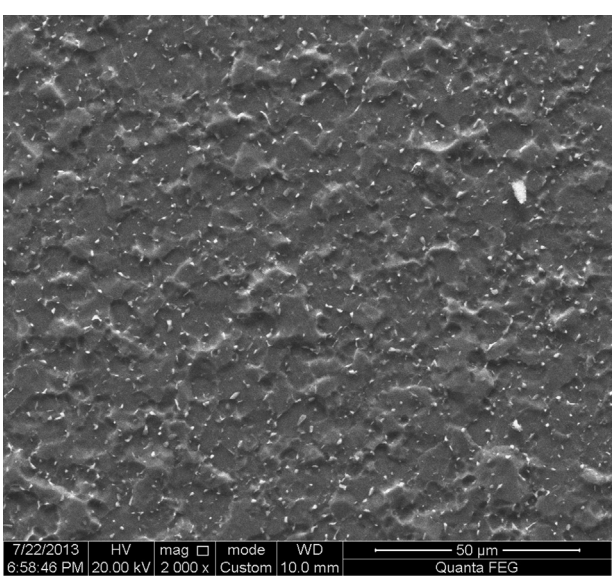


**Fig. 1.** SEM micrograph of Ti6Al4V alloy with the equiaxed structure.

**Table 1**
The multi-step decreasing load creep procedure.

| Step no. | Load (N) | $\sigma_i$ (MPa) | Holding time (s) |
|---|---|---|---|
| 1 | 1212 | 101 | 6 |
| 2 | 972 | 81 | 8 |
| 3 | 702 | 58.5 | 12 |
| 4 | 540 | 45 | 10 |
| 5 | 420 | 35 | 23 |
| 6 | 300 | 25 | 45 |
| 7 | 180 | 15 | 108 |
| 8 | 90 | 7.5 | 130 |
| 9 | 60 | 5 | 3258 |

$\sigma_i$: stress.

## 3. Results and discussion

### 3.1. Calculation of creep strain and creep rate

In C-L creep tests, the creep strain was acquired by eliminating the strain accumulated in loading stage from total strain. For C-S creep tests with pre-strain of 0.02 in different SRT time, the initial stresses are much the same in the beginning of SRT stage since the desire strain was applied in a constant strain rate. Thus, the initial stress relaxation behavior follows the same time-dependent law. This ensures that the creep strain accumulated in different SRT time is a fixed value. After each SRT test, certain amount of strain would recover upon unloading. The recovery strain consists of both recovery elastic strain and an elastic strain, and the remaining is viscous strain, as summarized by Sinha and Sinha [10]. In this study, the applied constant strain of 0.02 includes elastic