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# Effect of pre-deformation on creep age forming of 2219 aluminum alloy: Experimental and constitutive modelling

Youliang Yang[a], Lihua Zhan[a,b,c,*], Rulin Shen[a,b], Xuni Yin[a], Xicai Li[a], Wenke Li[a,c], Minghui Huang[a], Diqiu He[a]

[a] School of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China
[b] State Key Laboratory of High-Performance Complex Manufacturing, Central South University, Changsha 410083, China
[c] Nonferrous Metal Oriented Advanced Structural Materials and Manufacturing Cooperative Innovation Center, Central South University, Changsha 410083, China

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ABSTRACT

Applying pre-deformation to high strength aluminum alloy has significant impacts on shape formation and mechanical properties of component in creep age forming process. The suitable degree of pre-deformation can not only improve forming efficiency, but also attain sound mechanical properties. This paper experimentally investigates the effects of pre-deformation on creep strain, mechanical properties and microstructures of AA2219. The results show that pre-deformation can prolong the duration of primary creep stage and considerably facilitate creep strain. Through mechanical property tests, it is found that pre-stretched AA2219 possesses a high-performance "peak ageing strengthening region" with little fluctuation during creep ageing of 7–13 h. Further examinations by TEM tests indicate that this is due to the fact that the morphology of precipitates in this region remains unchanged without remarkable coarsening. Based on microstructural evolution and ageing strengthening theory, a set of physically-based creep ageing constitutive model is proposed. The developed model takes into account the effect mechanism of pre-deformation and incorporates the coupled interactions of microstructure, yield strength and creep strain. A good agreement between predicted and experimental values is achieved, which verifies the accuracy of the developed model. Hence, it provides the theoretical basis for the prediction of shape and properties in creep age forming of large-scale panel component.

## 1. Introduction

Creep age forming (CAF) is a new sheet metal forming method that utilizes the creep/stress relaxation effects and ageing heat treatment strengthening response of high strength aluminum alloy [1]. This method is suitable for fabricating aircraft skin, fuselage and rib-stiffened tank plate of rocket as well as other large components in aerospace industry [2,3]. In CAF process, part of the component's elastic deformation is converted into permanent creep deformation, which determines the final shape of the component. Meanwhile, the internal microstructure of the material is changed, enhancing the component's mechanical performance [4]. Nevertheless, due to the two following reasons, the component often finds it difficult to simultaneously satisfy required shape and performance. The first reason is the big activation energy difference between shape formation and properties improvement. For instance, the deformation activation energy of AA2219 is 99 *KJ/mol*, while the precipitation activation energy of strengthening phase ($Al_2Cu$) corresponds to 52 *KJ/mol*[5]. This leads to creep deformation hysteresis of the component or material overageing. The second one is the non-uniform driven energy field for properties change. The internal stress field gradient of the component, which is big in size and complicated in structure, varies drastically during bending process. In addition, the uneven temperature distribution of manufacturing environment composed of autoclave and mould may result in the non-homogeneous precipitation of strengthening phase and stress orientation effect. So how to accomplish the collaborative manufacturing of component with accurate configuration and required properties has important theoretical and practical meanings. Previous studies have shown that introducing pre-deformation into plate before ageing heat treatment benefits for the reduction in quench-induced stress and the improvement in material's strength [6,7]. Therefore, pre-deformation is expected to an effective way in expanding the collaborative manufacturing window of "shape-properties".

Extensive investigations have been carried out on the impacts of pre-deformation on the microstructures and mechanical properties of

* Corresponding author at: School of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China.
*E-mail address:* yjs-cast@csu.edu.cn (L. Zhan).

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materials in artificial ageing [7–9], and on the influences of various treatment methods on pre-strained alloy plate [10–14]. Whereas there are few published literatures about the effects of pre-deformation on creep age behavior or shape forming behavior. Our previous study found that the introduction of pre-deformation can reduce the amount of springback, enabling the radius of deformed plate gets closer to the target value [15]. Zhou et al. [16] discovered that strengthening phase changes from {111} plane $\theta'$ phases to {111} plane $\Omega$ phases after introducing pre-deformation to 2124 aluminum alloy and the material strength is increased by 9% without much loss of elongation. Zhao et al. [17] concluded that the creep mechanism of water-quenched 2124 aluminum alloy is dominated by dislocation multiplication first and then dislocation multiplication-annihilation balance. But in the case of pre-deformed materials, it is dislocation annihilation. In the light of literature review aforementioned, current research mainly focus on aspects of creep characteristics and creep mechanisms. There are no publications concerning the creep ageing constitutive model of high strength aluminum alloy that takes into account the effect mechanism of pre-deformation. Therefore it is of vital significance to work on this subject.

Since its favorably comprehensive performance, especially excellent weldability and elevated temperature and cryogenic properties, 2219 aluminum alloy is widely used in rib-stiffened rocket tank plate, such as Saturn 5 [2] and Ariane 5 [18]. Its properties can be obtained through a complex thermomechanical treatment, which ends with a solution treatment, a quench, a plastic deformation and artificial ageing treatment, with the usual precipitation sequence:-

$\text{solid solution} \rightarrow \text{GP zones} \rightarrow \text{metastable}\theta'' \rightarrow \text{metastable}\theta' \rightarrow \text{stable}\theta(Al_2Cu)$.

The mechanical performance of AA2219 with 7% pre-deformation is substantially increased and more widely applied in the practical application.

The aim of this study is to establish a physically-based creep ageing constitutive model for 7% pre-deformation AA2219, so as to accurately predict the evolutions of “shape-properties” in creep age forming of this material. A series of experiments are designed to investigate the influences of pre-deformation on creep strain, yield strength and microstructure of AA2219 alloy. According to ageing kinetics, creep deformation mechanism and dislocation theory, a set of creep ageing constitutive model is derived. Furthermore, the application of model and strengthening response of material are discussed in detail.

## 2. Experimental programme

### 2.1. Material

The virgin material was hot-rolled AA2219 plate of 2 mm thickness whose chemical composition is listed in Table 1. Creep samples with the gauge of 50 mm were machined out in parallel with the rolling direction of as-received plate (Fig. 1). Then samples were subjected to solution treatment in the electrical resistance furnace for 30 min at 535 °C, followed by water quenching at ambient temperature. For comparison, some of samples were stretched along the rolling direction with the amount of 7% after water quenching.

### 2.2. Experimental methods

Uniaxial tensile creep ageing tests were conducted with RMT-D10 electronic creep testing machine, at temperature of 165 °C under various stress levels (120, 150 and 180 MPa). The duration for tests are 0, 1, 3, 5, 8, 11 and 13 h, respectively. Room temperature tensile tests were performed using a CMT-5105 machine operating at a constant speed of 2 mm/min. For each condition, three samples were made to obtain an average value. Microstructure observations were carried out with a JEOL-2010 Transmission Electron Microscope (TEM) operating at 200 kV. The TEM specimens were prepared by cutting 10 mm×10 mm×0.5 mm (L×W×T) blocks from creep-aged samples. Then the blocks were thinned to 80 µm, punched into discs of 3 mm diameter. Last, the discs were twin-jet-electro-polished with a mixture of 70% methanol and 30% nitric acid at −35 ~ −25 °C cooled by liquid nitrogen. Characteristic parameters of precipitates in TEM images were statistically measured by the “image-pro plus” (a metallographic analysis software) in different view fields.

**Table 1**
Chemical compositions of 2219 aluminum alloy (mass fraction, %).

| Cu | Mg | Mn | Si | Fe | Ni | Zr | Ti | Al |
|---|---|---|---|---|---|---|---|---|
| 5.24 | 0.028 | 0.27 | 0.042 | 0.13 | 0.03 | 0.14 | 0.065 | Bal. |

## 3. Experimental results

### 3.1. Creep strain behavior

Fig. 2 depicts the creep strain curves of pre-deformed AA2219 at temperature of 165 °C under applied stresses of 120, 150 and 180 MPa for 11 h. It can be seen that all creep strain curves exhibit increasing trend with extension of time. Comparisons of creep behaviors between pre- and non-deformed AA2219 are shown in Fig. 3. Under the two circumstances, the curves show typical primary creep stage and steady-state creep stage [19], which are separated by the dotted lines (Fig. 3(a)). Obviously, the pre-stretched material has greater creep strain than that of non-stretched counterpart. For instance, after 11 h of ageing, creep strain of the former is 3.5 times than that of the latter. Further analysis indicates that it is mainly caused by much creep strain generated in primary creep stage. In the vicinity of 1 h ageing, the creep curve of non-deformed sample enters into steady-state creep stage and corresponding creep strain is accumulated up to 0.078%. But it takes 4 h for pre-deformed sample to reach steady-state creep stage with creep strain of 0.355%. It demonstrates that pre-deformation can extend the duration of primary creep region and greatly accelerate the generation of creep strain in this stage. This kind of “primary creep” feature owing to the effect of pre-deformation is extremely beneficial since it introduces more of creep deformation to retain the shape of plate after forming. Additionally, it can be observed from Fig. 3(b) that the creep strain rate of pre-stretched AA2219 alloy in primary creep stage is significantly larger compared with non-deformed alloy, which further indicates pre-deformation has positive effects on creep strain. The main reason is that at the initial stage of creep ageing, a large number of movable dislocations slip in pre-deformed sample, resulting in rapid increase of creep strain.

### 3.2. Mechanical property

Fig. 4 is the evolution of yield strength of pre-deformed AA2219 aged at 165 °C under various applied stresses. Overall, the yield strength of material increases quickly and then remains approximately unchanged with the increase of ageing time. When applied stress is 150 MPa, the yield strength augments rapidly before 4 h ageing, and then continues to increase slowly up to peak value of 379.3 MPa at 8 h. After peak value, the yield strength keeps almost constant, reaching 376.3 MPa at 13 h. From the above analysis, the yield strength change of pre-deformed material can be mainly divided into “0–7 h under ageing performance growth region” and “7–13 h peak ageing strengthening region”. The “peak ageing strengthening region” has the feature of high strength with low fluctuation, which is different from the non-deformed materials that possess only a short time of peak ageing zone. This characteristic contributes to extending the collaborative manufacturing window of “shape-properties” of plate in CAF process. That means properly prolonging the forming time can reduce springback amount and improve forming precision of plate without loss of