# EFFECT OF TRACE-ELEMENTS ON CREEP BEHAVIOR OF PURE ALUMINUMS AT A LOW TEMPERATURE

**Masataka MAEHARA, Keisuke ISHIKAWA and Yasuo KOBAYASHI**

Department of Mechanical Engineering, Toyo University,
Kujirai, Kawagoe, Saitama, Japan

**ABSTRACT** We investigated creep behaviors of pure aluminums with trace-elements under a constant applied stress condition at a low temperature, where neither atomic diffusion nor the recrystallization is active. Pure aluminums show a primary, a secondly and a ternary creep even at a low temperature. Effect of the trace-elements was clearly observed on the secondly creep rate and the time to rupture. The aluminum including more trace-elements has a slower secondly creep rate and a longer life. Microscopic effect of the trace-element would appear on the cell structure developed through the motion of dislocations.

**Key words:** *creep, pure aluminum, trace-element, low temperature, constant applied stress*

## 1. Introduction

Aluminum has a high electric conductivity and a good ductility at lower temperatures. Aluminum alloys are widely used as structure materials like duralumins. On the other hands, pure aluminums have recently been given attention to the application of the electronic technology and would be a promising lighter stabilizer instead of a copper for superconductors[1]. Pure metals, however, are so soft that it might be liable to creep even at a low temperature. Most studies on creep have been concentrated at high temperature because many creep phenomena have been observed at the restricted temperature[2]. On the contrary, the study on lower temperature creep has been rarely found[3]. We have observed a constant creep rate for pure aluminums even at a low temperature, where neither atomic diffusion nor recrystallization takes place. We investigated the effect of trace-elements in pure aluminums on creep behaviors at a lower temperature. The trace-elements have interesting effect on creep behaviors of pure aluminums.

## 2. Experimental procedures

### 2.1 Materials

The chemical composition of the materials is shown in Table 1. The round shape specimen has the dimension of 15mm in gauge length with a diameter of 5mm. All specimens for the creep tests were homogenized at 773K for 1 hour in air after mechanical processing.

**Table 1**. Chemical composition of pure aluminums tested (mass ppm)

| Symbol | Si | Fe | Cu | Ti | Mg | Total impurities |
|---|---|---|---|---|---|---|
| a | 2 | 1 | 1 | --- | 1 | 5 |
| b | 3 | --- | 1 | 1 | --- | 5 |
| c | 37 | 21 | 3 | --- | --- | 61 |
| d | 23 | 25 | 22 | 52 | --- | 122 |

### 2.2 Apparatus and measurement

Creep tests were conducted at a constant applied stress in simple tension. The applied stress was kept constant within the errors of 1%, during the creep teat. The test temperature was a room temperature around 293K, where was below half the melting point of aluminum. The elongation of the gauge length was measured with the laser extensomer whose minimum resolution was less than 50 $\mu$m. The measured elongation was stored in a personal computer on real time and converted into the true strain against the creep time. All creep tests were carried out up to rupture.

## 3. Experimental results

### 3.1 Creep strain changes at a constant applied stress

Fig.1 shows creep behaviors of pure aluminums at the respective applied stress of 0.9 tensile strength $(\sigma_B)$. The creep curves are divided into three regions, a primary, a secondly and a ternary creep. The higher the purity, the shorter the rupture time at the same applied stress ratio. Each rupture strain (the creep ductility) depends upon the impurity.

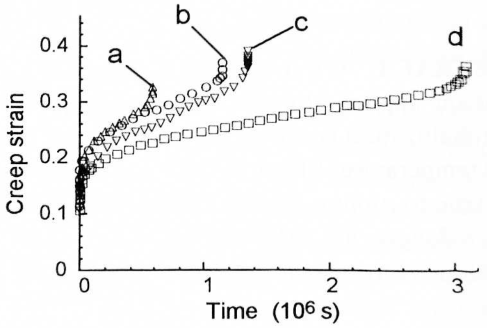

**Fig.1** Creep strain v.s. time curves for pure aluminums at the same applied stress ratio $(0.9\sigma_B)$.

### 3.2 Primary creep behavior

An initial creep strain consists of an instantaneous and a primary creep strain. The instantaneous strain is constant against the creep time. The primary creep strain, however, increases with the time. Several time-laws are proposed for the primary creep[4]. We have scrutinized our experimental results compared with the proposed equations. There is a better agreement with a logarithmic time-law than a power function or an Andrade's time-law. The experimental data and the logarithmically calculated curves of the primary creep strain are shown in Fig.2.

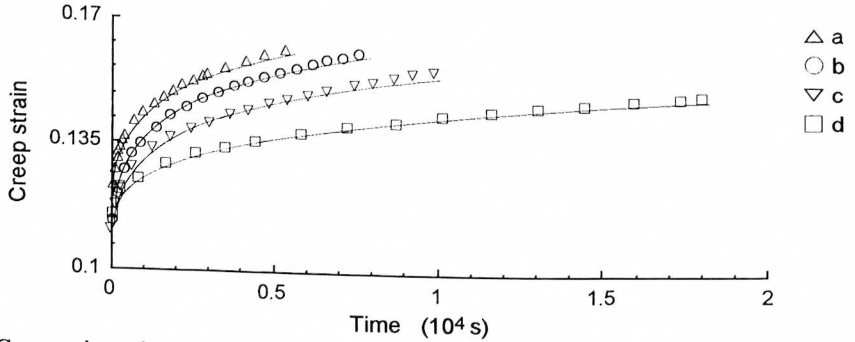

**Fig.2** Comparison between the experimental data and the logarithmic creep curve for pure aluminums at the same applied stress ratio $(0.9\sigma_B)$.

### 3.3 Creep strain rate against creep time

The secondly creep is an important information for the theoretical analysis of the plastic deformation mechanisms. Fig.3 shows the creep strain rate against the creep time for the respective

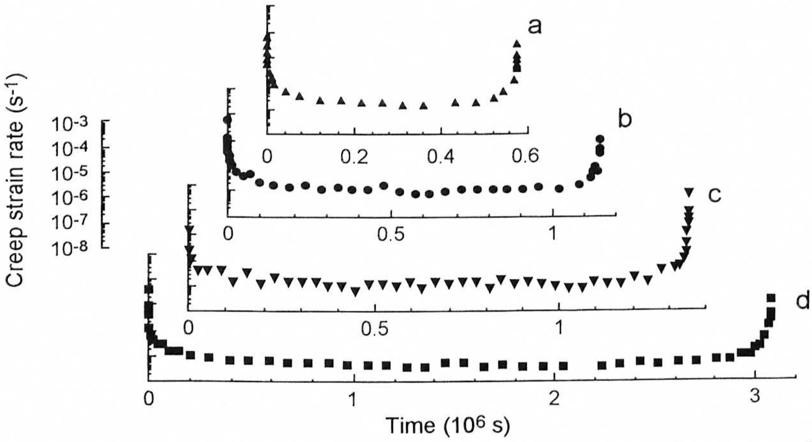

**Fig.3** Creep strain rate v.s. time curves for pure aluminums at the same applied stress ratio (0.9 $\sigma_B$).

aluminums. The constant strain rate creep named as a steady state creep has been usually observed at higher temperatures through the balance between the work hardening and the recovery process assisted by the atomic diffusion[2,4]. The apparent steady state creep, however, is observed in these experiments within just the work hardening and its duration depends upon the purity and the applied stress. The lower the purity, the longer the duration and the slower the constant creep rate at the same applied stress ratio.

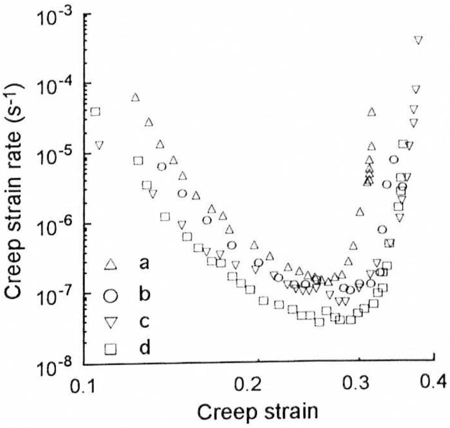

**Fig.4** Creep strain rate v.s. creep strain curves at the same applied stress ratio (0.9 $\sigma_B$).

### 3.3 Creep strain rate against creep strain

When the creep strain rate is drawn against the creep strain, the strain rate shows minimum and is not constant as shown in Fig.4. The minimum strain rate depends upon the purity as well. Greater part of the total creep strain is spent prior to the minimum strain rate. The definition of the secondly creep depends upon its expression of the strain rate curve.

### 3.4 Creep life

We defined the rupture time as a creep life. Relationship between the creep life and the applied stress would be expressed by $T_r \propto \sigma^{-m}$, where $T_r$ is the creep life and $m$ is a material constant[4,5]. In this experiments, the relationship has been confirmed for the respective materials. Impurity dependence of the stress exponent, $m$ is shown in Fig.5.

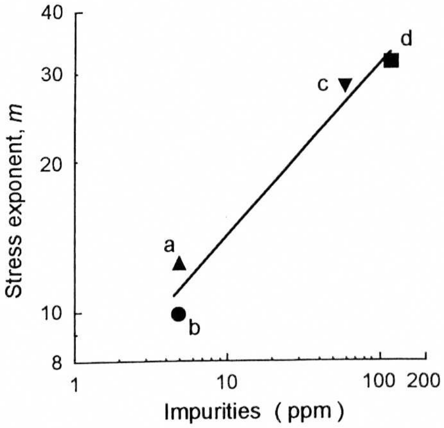

**Fig.5** Effect of impurities on stress exponent, *m*.

## 4. Discussion

### 4.1 Effect of impurities on the creep behavior

Low temperature creep strain have been often described by $\alpha\ln(\beta t+1)+\gamma$, where $\alpha$ , $\beta$ and $\gamma$ are the constants against the creep time[4,7]. We defined $\beta$ to a unity for the time in second. $\gamma$ is constant for each material, that is, $\gamma$ is estimated as an instantaneous strain and would be evaluated by the Young's modulus of aluminum. On the contrary, $\alpha$ has the applied stress dependence[6]. It is shown in Fig.6, where the applied stress is normalized with the tensile strength ($\sigma_B$). The value of the $\alpha$ is proportional to the applied stress ratio, regardless of the purity. In other words, it is concluded that the logarithmic time-law of the primary creep strain could not be affected by the impurity less than 122ppm.

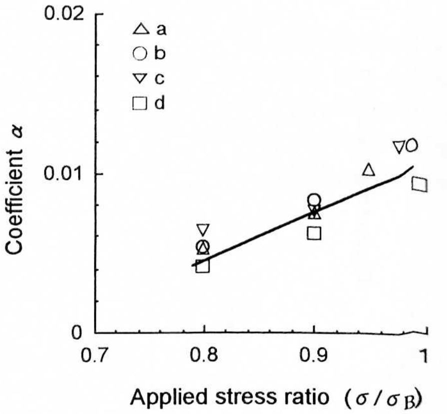

**Fig.6** Relationship between $\alpha$ and applied stress ratios for respective materials.

While the total impurities are increased, strain rates (the steady state strain rate and the minimum strain rate) are reduced and the creep life is prolonged as shown in Fig.3 and 4. Effect of total impurities on the both strain rates and the creep life are shown in Fig.7 and 8. It is found that the strain rate decreases in $\dot{\varepsilon}_s = \lambda C^{-n}$ and the creep life increases in $T_r = \mu C^p$ , respectively. $\dot{\varepsilon}_s$ is the steady state strain rate. $C$ is the content of the total impurities. $n$ and $p$ are material constants. λ and $\mu$ are constant, regardless of the impurity. Both equations lead to the following relation,

$$\dot{\varepsilon}_s \times T_r = \lambda\mu C^{-n+p} = AC^{-n+p} \qquad (1)$$

where A is constant. It is rewritten further as follows,

$$\frac{\dot{\varepsilon}_s \times T_r}{C^{-n+p}} = A = constant \qquad (2)$$

The effect of the impurities on $\dot{\varepsilon}_s$ and $T_r$ of the pure aluminum is given by Eq.2. Fig.9 shows the

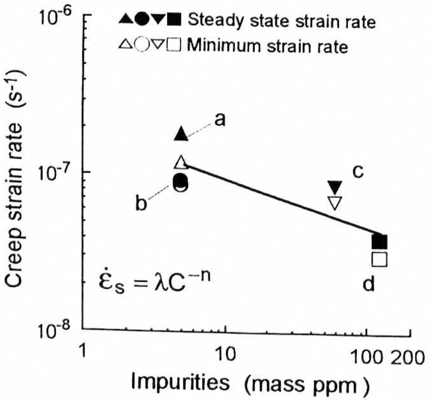

**Fig.7** Effect of total impurities on strain rates.

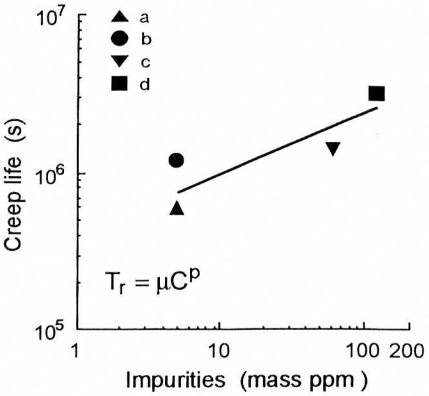

**Fig.8** Effect of total impurities on the creep life.

relationship between $\dot{\varepsilon}_s \times T_r$ and $C^{-n+p}$. For the similar material, $n=p$ should be observed, since $\dot{\varepsilon}_s \times T_r = constant$[7].

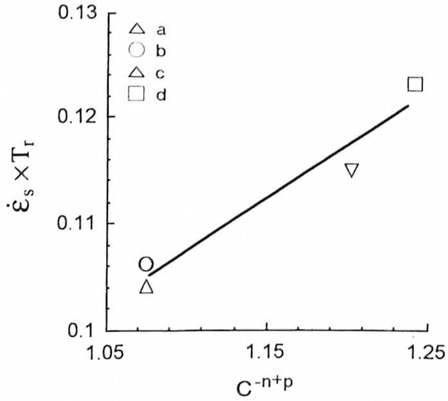

**Fig.9** Effect of the trace-element on $\dot{\varepsilon}_s \times T_r$.

### 4.2 The role of the trace-elements

Many dislocation theories have been proposed to the creep behaviors[4,7]. The low temperature creep is brought about by just the motion of dislocations, since no atomic diffusion takes place. During the creep, dislocations emitted from the sources move on their glide planes until they are led to obstacles eventually. The microscopic hardened region would be produced in the matrix of the material, since immobile dislocations are accumulated. The aluminum with the trace-elements is a substitutional solid solution metal. When a dislocation is moving over the solid solution atom, it never fails to receive either an attractive or a repulsive force from the trace-elements. Thus, the dislocation line must be bent by a frictional force caused by an interaction between the dislocation and the trace-elements. The bended dislocation lines are apt to take the tangled distribution resulted in the cell structure[2]. These cell structures are not easy to deform through the strong dislocaiton-dislocation interaction. The trace-elements in low temperature creep would have an effect on the cell structure itself, too.

In particular, we point out the subtle differences among Fe, Mg and Ti as a trace-element. Difference among them has appeared on the exponent, *m* of the creep life. It would be observed for material *a* and *b* as shown in Fig.5. It could come from that the atomic diameter of Fe in aluminum is smaller than that of Ti. Mg is larger than Ti[8]. The dislocation line is received larger effects from Fe and Mg. The dislocation lines might be bent more easily near Fe and Mg atom.

### Conclusions

We could get the below conclusions from the experiments on the creep behavior of pure aluminums with 5 to 122 ppm impurities.

1. The primary, the secondly and the ternary creep are clearly observed for the pure aluminums under a constant applied stress condition at a low temperature.
2. Effect of the trace-elements is recognized on the various creep behavior of pure aluminums.
3. The apparent steady state creep is observed against the creep time even at a low temperature.
4. The constant strain rate is not recognized against the creep strain, but the minimum strain rate is observed.
5. The subtle differences in the effect of the trace-elements on the creep behavior are understood through the effect of the impurities on the mobility of dislocations.

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