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FINAL REPORT

CREEP OF AU-4G1 ALUMINUM ALLOY UNDER INCREMENTAL VARIATION IN STRESS

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ABSTRACT

Incremental loading tests were performed on AU-4Gl aluminum alloy-sheet specimens subjected to tensile creep at 473°K. Tests consisted of changing the axial stress by a small amount, by either loading or unloading, during primary creep. Results were similar to those obtained previously on commercially pure aluminum. Incremental strain response due to a small increase in stress was essentially linear viscoelastic, while unloading caused cessation of creep straining for a time, following by linear viscoelastic creep. Material stiffness increased during creep, indicating that strain hardening was taking place. For axial stress in the plastic range of the material, the modulus increased with time from an initial inelastic value and approached the elastic modulus.

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LIST OF SYMBOLS

E	- elastic modulus
m, n	- integer
P, Q	- linear differential operators in Eq. (1)
p_m, q_m	- creep parameters
t	- time
t_o	- time of stress-change
Δt	- creep time after stress-change
Δt_{rec}	- incubation time after negative stress-change
ε	- strain
ε_{creep}	- creep strain
ε_o	- strain at t_o
$\Delta\varepsilon$	- strain increment
σ	- applied stress
σ_o	- initial stress
σ_1	- $= \sigma_o + \Delta\sigma$
$\Delta\sigma$	- stress increment

NOTE ON UNITS

Whenever practical the units adhered to in this report correspond to the International System of Units, as defined by the Eleventh General Conference of Weights and Measures, 1960, and subsequent Conferences. Following are a number of conversion factors which will be useful in reading this report.

$$0.1017\ \mathrm{kg/mm^2} = 1\ \mathrm{MN/m^2}$$

$$1{,}450\ \mathrm{psi} = 1\ \mathrm{MN/m^2}$$

$$-\ 273.15\,^{\circ}\mathrm{C} = 0\ ^{\circ}\mathrm{K}$$

$$\frac{1}{3600}\ \mathrm{hr} = 1\ \mathrm{sec.}$$

INTRODUCTION

The research reported herein constitutes a continuation of the program previously reported in Refs. 1 and 2. These papers presented the results of experiments performed to examine the effects of increments of stress on the creep response of commercially pure aluminum in the low strain range. One of the objectives of the investigation was to determine whether the change in strain and strain rate caused by an increment of stress could be described by a linear viscoelastic type of creep relation, as suggested in Ref. 3. A further aim was to ascertain whether the elastic modulus of the material changes during creep, as hypothesized by creep buckling theories such as that of Ref. 4. These theories assume that creep straining of columns and plates causes a decrease of the material modulus so that the flexural stiffness for small lateral displacements is reduced with time.

The tests in Refs. 1 and 2 were performed on specimens of annealed commercially pure aluminum subjected to uniaxial tensile creep at $473^{\circ}K$. This material was chosen for the stability of its mechanical properties with time, rather than for engineering applicability. For commercially pure aluminum strain response following a small stress change was essentially linear visco-elastic. However material stiffness was found to increase due to strain-hardening during creep, approaching the elastic value.

An important question which remained to be answered was whether the behavior found in commercially pure aluminum also occurs in alloys of aluminum, especially those commonly used for aircraft structures and in the leading end of some jet-engine compressors. For the present research the material chosen for investigation was AU-4G1 aluminum-alloy sheet, an aircraft alloy similar to 2024-T3 aluminum alloy. This material generally displays quite different mechanical characteristics than does comercially pure aluminum. One of the important differences which was considered is that the strength of the alloy at elevated temperatures is time-dependent, in strong contract to the pure metal.

LINEAR VISCOELASTIC EQUATION FOR CREEP AFTER INCREMENTAL CHANGE IN STRESS

In Ref. 3 a linear viscoelastic equation was chosen to describe the effect of an incremental change in stress on creep behavior of metals in the form

$$P(\Delta\sigma) = Q(\Delta\varepsilon) \tag{1}$$

where P and Q are linear operators of the form

$$P = \sum_{o}^{n} p_m \frac{\partial^m}{\partial t^m}, \quad Q = \sum_{o}^{n} q_m \frac{\partial^m}{\partial t^m} \quad \text{respectively.}$$

$$m = 0, 1, 2.....n$$

and $\Delta\sigma$ and $\Delta\varepsilon$ are the increment of stress and the corresponding increment of strain respectively (see Figure 1). If $\Delta\sigma$ is much smaller than the stress before the stress-change σ_o, and Eq. (1) is assumed to hold only near the time, t_o at which the stress was changed, then p_m and q_m are functions of σ_o and t_o only.

Specifically, Eq. (1) determines the additional creep occurring after the stress-change, relative to the creep which would have occurred if the stress had remained at the original level. Eq. (1) is quite general and solutions corresponding to or approximating many empirical creep relations can be obtained from it, depending on the number of terms chosen in the differential equation. For example if $n = 2$, $q = 0$, and initial conditions are as stated, Eq. (1) gives the strain resulting from the stress increment as

$$\Delta\varepsilon = \Delta\sigma\left[\left(\frac{p_1}{q_1} - \frac{p_o q_2}{q_1^2}\right) + \frac{p_o}{q_1}\Delta t + \left(\frac{p_2}{q_2} + \frac{p_o q_2}{q_1^2} - \frac{p_1}{q_1}\right)\exp\left(-\frac{q_1}{q_2}\Delta t\right)\right] \qquad (2)$$

as obtained in Ref. 3. In Eq. (2) $\Delta t = t - t_o$.

TEST SPECIMENS

Tensile test specimens were machined from a sheet of AU-4G1 aluminum alloy of 4mm nominal thickness. The specimen axis was parallel to the rolling direction of the sheet. Dimensions of the test specimens are shown in Figure 2. The reduced section was machined to a width of 12.50 mm and a length of 245mm.

TEST EQUIPMENT AND PROCEDURE

The creep-testing machine used in the program and shown in Figure 3 was designed to apply deadweight loads of up to 25,000N in tension with the aid of a beam-loading mechanism, with a lever-arm ratio of 20:1. Hardened knife-edges are used in the pivot of the beam, and at the specimen and weight-cage attachment points. The beam and weight-cage are balanced by a counterweight. Applied load was measured by use of a strain-gage load cell in series with the test specimen. The ends of the test specimen are clamped in tension grips, hinged in mutually perpendicular directions in the horizontal plane in order to permit complete freedom of alignment when the load is applied.

The tubular furnace used in the creep-testing machine is 320mm in length, with an internal diameter of 75mm. The furnace has a capacity of 1,275^{o}K. In the present program the automatic control unit maintained the temperature at a given point on the test specimen constant with time within ± 1^{o}K, and the maximum temperature difference along the specimen was 4^{o}K. Specimen temperature was measured with iron-constantan thermocouples of 0.25mm diameter (30gage) wire spot-welded to the specimen.

Strains in the test specimens were measured by use of a mechanical extensometer connected to an LVDT(linear variable differential transformer) which has a linear range of ± 2.5mm.

Each creep specimen was exposed to the test temperature for 1/2 hour prior to test, in order to stabilize the temperature distribution in the furnace and the strain transducer. After exposure, a tensile stress of 220 MN/m^2 was applied to the specimen at a loading rate such that the strain rate obtained was approximately 33 x 10^{-6}/sec. Autographic recording of stress and strain permitted determination of the value of the strain at the instant the specimen was fully loaded.

An incremental change in axial stress was applied after 3 hours of creep. The stress increment never exceeded 6% of the initial creep strees. Positive stress change was achieved by adding small weights to the weight cage, negative stress increment by removing a small container of weights without disturbing the cage. The test was allowed to continue until substantial additional creep had occurred.

RESULTS AND DISCUSSION

Stress-Strain and Constant-Stress Creep Behavior

General results obtained during short time stress-strain tests and from creep tests conducted at constant tensile stress will now be presented. These results served as reference data for creep results obtained under varying stress conditions.

The stress-strain curve obtained for the material at $473^{o}K$ at a strain rate of approximately 33 x 10^{-6}/sec. is shown in Figure 4. The mean value of the elastic modulus was 62,000MN/m^2, with a standard deviation of 5 percent. Mean values obtained for proportional limit stress and 0.2% offset stress were 140 MN/m^2 and 303 MN/m^2 respectively. The average curve obtained from creep strain data under a constant tensile stress of 220 MN/m^2 at $473^{o}K$ is plotted against time in Figure 5. The results shown in Figures 4 and 5 are generally in accord with published data on 2024-T3 aluminum-alloy material at the test temperature (Ref. 5).

Creep Resulting from an Increment of Axial Stress

Results showing the effect of a small positive or negative change in stress on creep behavior will now be presented. The range of stress increments was from 2 to 6% of the initial stress. Data on individual tests are given in Table 1.

Positive Stress-Change

Creep curves obtained after application of a positive increment of stress $\Delta\sigma$ are shown as solid lines in Figures 6 and 7. In the figures $\varepsilon - \varepsilon_o$, the total strain accumulated following the stress change, is plotted against Δt, the time after the change in stress. The time of stress-change t_o is equal to 3 hours in all cases. The dashed lines represent creep at the initial stress σ_o, extrapolated beyond t_o. The creep curve after the stress-change displays an accelerated initial strain rate which decreases with time. Although the initial stress was in the plastic range of the material, the curve tends towards and becomes parallel to the original creep curve for σ_o. This result is not in agreement with results reported in Ref. 2, although it apparently does substantiate the conditions laid down in Ref. 6. For commercially pure aluminum under an increment of stress in the plastic range the curve tended towards the creep curve corresponding to the new total stress.

The additional creep $\Delta\varepsilon$ occurring as a result of positive stress-change (see Figure 1) is plotted in Figure 8 in the form of creep compliance $\Delta\varepsilon/\Delta\sigma$ against Δt. Curves in the form of Figure 8 are convenient for the evaluation of results with regard to linear viscoelastic behavior. A mean curve (dashed line) has been drawn through the data shown in the figure. The maximum scatter of the results about the mean curve is ± 20% of $\Delta\varepsilon/\Delta\sigma$. This amount of scatter is reasonable when the small magnitude of $\Delta\sigma$ and $\Delta\varepsilon$ is considered, as well as the scatter inherent in creep tests in general and is in accord with previous results (Ref. 2). The results obtained indicate an instantaneous strain due to the stress change, a transient period during which the creep rate decreases, and a steady state with constant creep rate. These three phases are similar in nature to the early stages of creep at constant stress, and correspond to the time-dependent terms in the linear viscoelastic creep relation Eq. (2).

It is apparent from the figure that, for the range of $\Delta\sigma/\sigma_o$ investigated, the creep obtained is linearly dependent on $\Delta\sigma$ in the sense of Eq. (2) and in this case also in the sense of Ref. 6 when allowance is made for scatter of data. Determination of the range of $\Delta\sigma/\sigma_o$ beyond which $\Delta\varepsilon$ is no longer linear in $\Delta\sigma$ remains to be completed in future work.

The instantaneous strain resulting from the stress change was linear in $\Delta\sigma$, as shown in Figure 8 and $\Delta\varepsilon/\Delta\sigma$ was on the order of the inverse of the elastic modulus. This result, which is due to strain hardening occurring during creep, has been discussed elsewhere with respect to creep mechanism (Ref.1) and creep buckling (Ref. 6). Suffice it to say that the present test results again did not reveal the low-valued inelastic modulus implied in Refs. 3 and 4.

Specific numerical values of the creep constants in Eq. (2) for the particular material and test conditions of the program are not of great practical importance. However in discussing the nature of the result it may be noted that the minimum incremental creep-rate p_o/q_1 is zero for $\sigma_o = 220 MN/m^2$, and presumably for lower initial stresses also. However it is likely to have finite values when the initial stress is high in the plastic range of the material. This result is somewhat inconclusive at present and additional tests must be carried out at higher values of σ_o in order to establish whether aluminum alloy behavior does or does not support the assumptions involved in the equation of state for creep (Ref. 4), which requires that $p_o = 0$, as pointed out in Ref. 3. The value of retardation time q_2/q_1 obtained from the experimental data was approximately 0.35 hour.

Negative Stress-Change

Creep curves representative of data obtained after a slight reduction in stress at $t_o = 3$ hours are shown in Figures 9 to 11. The stress was accompanied by an instantaneous negative strain of magnitude proportional to $\Delta\sigma$, and the modulus during the stress-change was equal to the elastic modulus E as expected. The instantaneous strain was followed by a period during which no strain was detected, after which creep strain resumed. The average incubation times Δt_{rec} to resumption of creep are plotted against the relative change in stress $-\Delta\sigma/\sigma_o$ in Figure 12. The line drawn through the experimental data in the figure corresponds to the relation

$$\Delta\sigma/\sigma_o = -F(\Delta t_{rec})^{0.84} \tag{4}$$

where F is a constant.

Incubation times for the alloy material were shorter than for pure aluminum, in line with the generally higher creep rates of alloys relative to the rate of creep of pure metals. The incubation or delay time is due to change in the rate of dislocation motion in the material as a result of the stress reduction. Dislocation velocity is strongly dependent on stress (Ref. 7) and is greatly reduced when part of the applied stress is removed. Although the reduction in the applied stress is small the resulting disarray in areas of dislocation concentration is considerable, with the result that dislocation motion ceases in these areas and further creep strain occurs when dislocations in other planes of the material lattice begin to move. This can happen more quickly in alloyed material because of the higher density of dislocation sources.

No transient phase, such as occurred after application of a stress increment, is observed in Figures 9 to 11 when creep recommenced after a decrement in stress. The resumed creep curve was parallel to the creep curve for σ_o, with a constant difference equal to the sum of the instantaneous strain and the strain at σ_o during the incubation time. It may be explained that a degree of relief of the strain-hardened condition induced at stress σ_o occurred during the incubation time, with the result that the equilibrium between the strain-hardening rate and the rate of vacancy diffusion remained unchanged and the subsequent creep rate was undisturbed and remained the same as at the initial stress. The results show that $\Delta\varepsilon$ is linearly dependent on the stress decrement in the range tested, as was the case for stress increment. Additional tests are required in order to determine the dependence of the creep constants on the value of initial stress σ_o.

Effect of Aging

AU-4G1 aluminum alloy exhibits an aging effect at elevated temperatures. At 473^oK the material 0.2% offset yield stress and the ultimate tensile stress increase as the material is exposed to temperature for approximately 4 hours. Thereafter the material undergoes overaging and the yield stress and ultimate strength decrease monotonically (cf. Ref.8). The effects of overaging were not discernible in results obtained during this investigation, since only one initial time t_o was used. The time at initial stress was 3 hours, close to the time of maximum strength. It would be of interest to compare these results with results of similar tests performed at much longer initial times, when the material would be in the overaged condition.

Although the duration of the present tests ranged from 4 to 7 hours, aging had no apparent effect on static and dynamic moduli or on values of the damping coefficient. (Methods used in measuring static and dynamic moduli and damping are described in detail in Ref. 1). This was to be expected. The dynamic modulus is generally insensitive to stresses and strains in the plastic range of the material. The static modulus and the damping coefficient have been seen to recover their elastic values due to strain-hardening during creep, and are therefore independent of the height of the stress-strain curve. These results were in complete agreement with those obtained in Ref. 1.

CONCLUSIONS

Results obtained from incremental load tests on AU-4G1 aluminum alloy-sheet specimens subjected to tensile creep at 473°K were presented and considered in terms of a linear viscoelastic analysis. Tests consisted of changing the axial stress by a small amount at a given time during primary creep.

Incremental strain response due to increase of axial stress up to 6% of the initial stress was essentially linearly viscoelastic. Small decreases of axial stress caused creep straining to cease for a time, following which the response was again linear viscoelastic. The magnitude of stress increment for which the incremental strain ceases to be linearly viscoelastic has yet to be investigated, as has the nature of the creep response when the initial stress is higher in the plastic range of the material, and when the time at initial stress is sufficiently long to cause overaging of the material.

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TABLE 1 - TEST CONDITIONS AND RESULTS FOR AU-4G1 ALUMINUM ALLOY SHEET SPECIMENS.

Specimen No.	Cross-sectional Area (mm^2)	σ_o (MN/m^2)	$\Delta\sigma$ (MN/m^2)	$\left\lvert\frac{\Delta\sigma}{\sigma_o}\right\rvert$	Δt (sec.)	$E \times 10^{-4}$ (MN/mm^2)		
						Load	Unload	Stress Change
B10	50.0	220.	+ 13.7	0.06	3600	6.2	6.3	6.2
B40	49.7	220.	+ 13.2	.06	5760	5.9	6.0	6.0
B42	50.5	220.	+ 08.8	.04	3600	6.3	6.3	6.3
B65	50.1	220.	+ 8.8	.04	3600	6.1	5.8	6.2
B32	51.1	220.	+ 4.4	.02	3600	5.8	6.0	6.0
B52	50.1	219.	- 12.9	0.06	8640	6.4	6.4	6.3
B47	51.3	228.	- 13.8	.06	7200	6.4	6.2	6.2
B50	50.8	220.	- 9.0	.04	7560	6.4	6.2	6.3
B11	51.0	222.	- 8.2	.04	7560	6.2	6.2	6.1
B12	50.9	218.	- 4.4	.02	14760	6.4	6.2	6.4
B44	51.0	224.	- 4.5	.02	6840	6.1	6.0	6.2

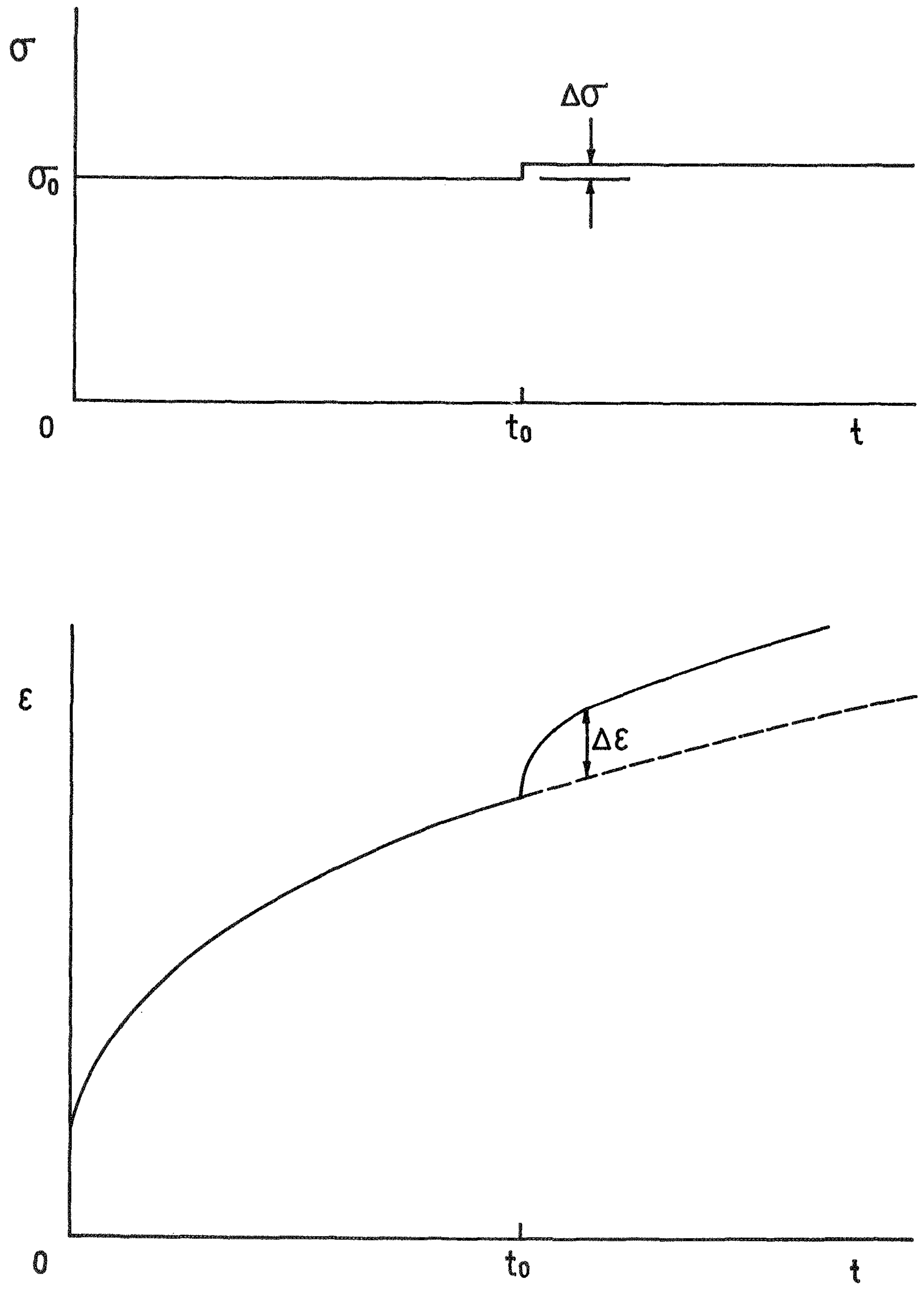
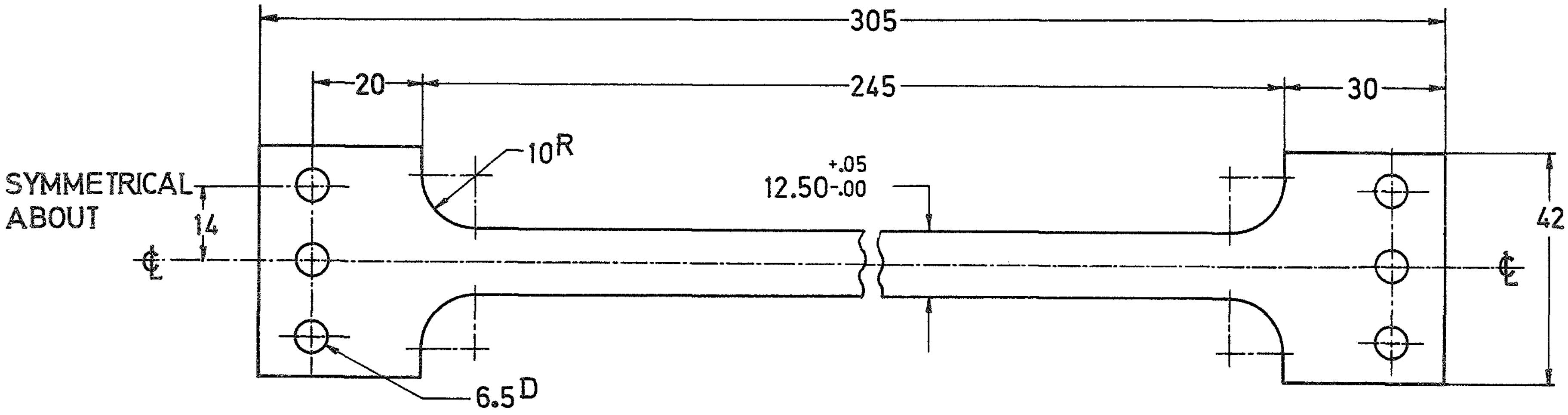


FIG. 1. EFFECT OF INCREMENTAL CHANGE IN STRESS ON CREEP BEHAVIOR



ALL DIMENSIONS MILLIMETERS
TOLERANCE (UNLESS INDICATED) : 0.25 mm

FIG. 2. CREEP TEST SPECIMEN, AU-4G1 ALUMINUM - ALLOY

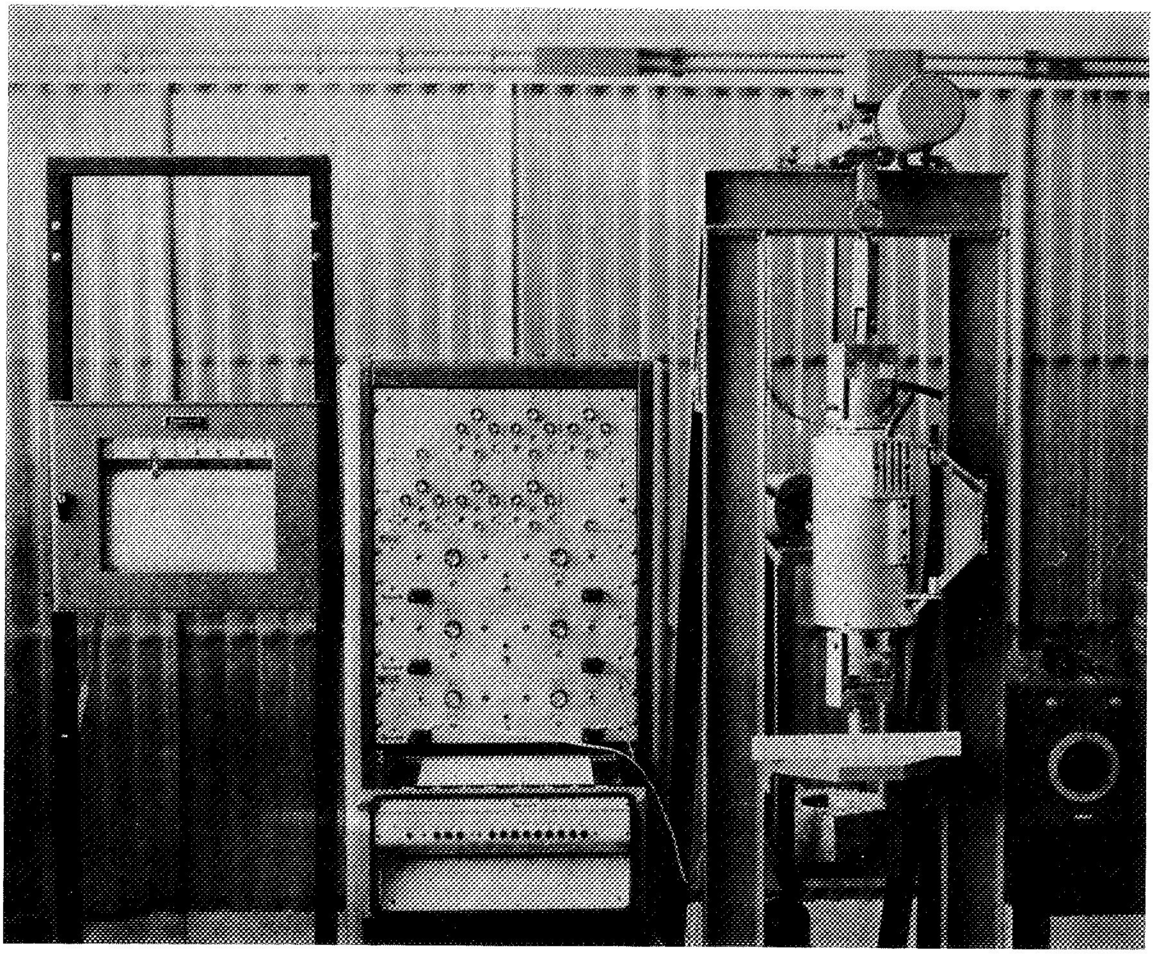


FIG. 3. EXPERIMENTAL SET -UP

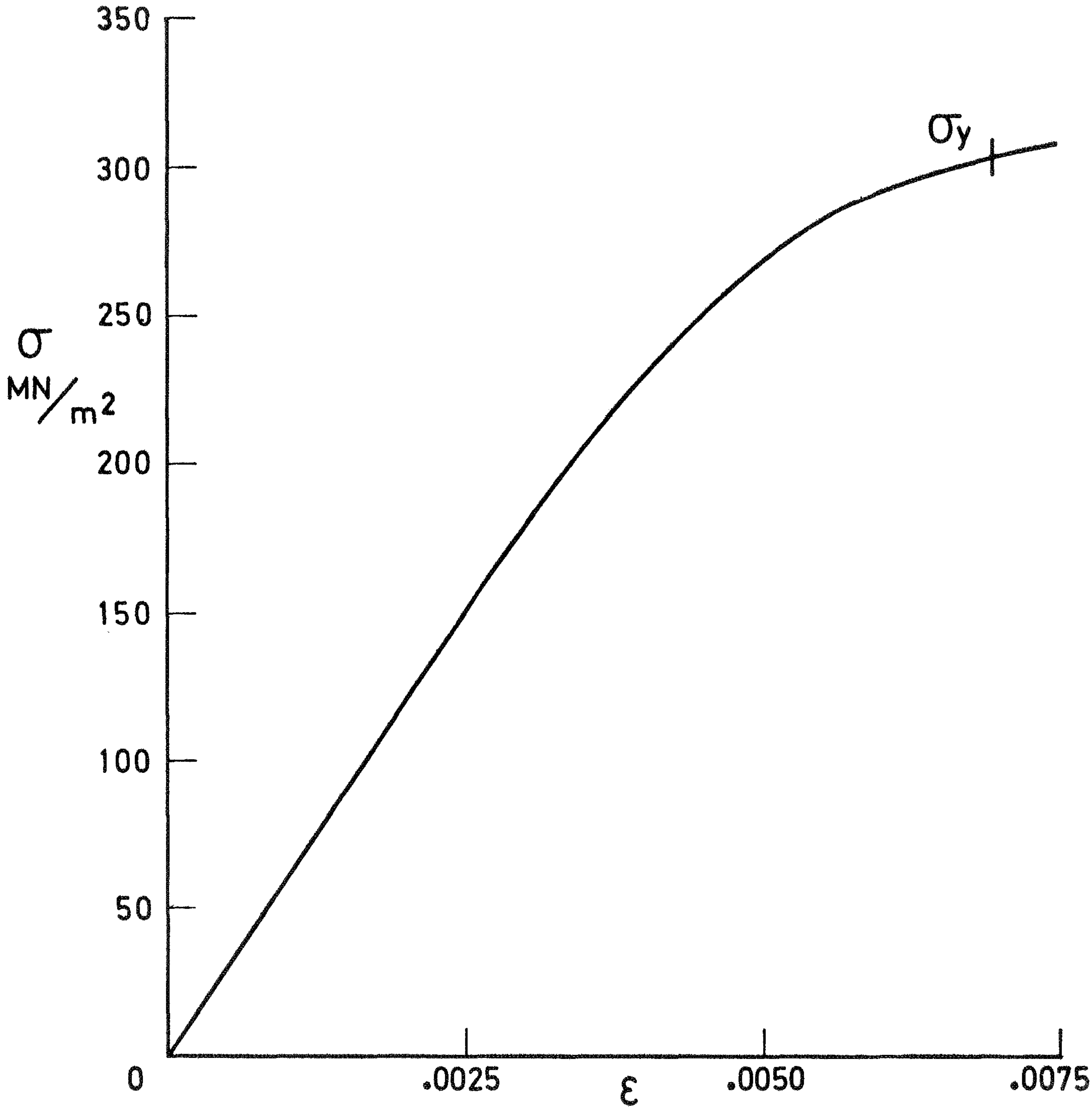


FIG. 4. TENSILE STRESS – STRAIN CURVE FOR AU-4GI ALUMINUM ALLOY AT 473°K, 1/2 HR EXPOSURE

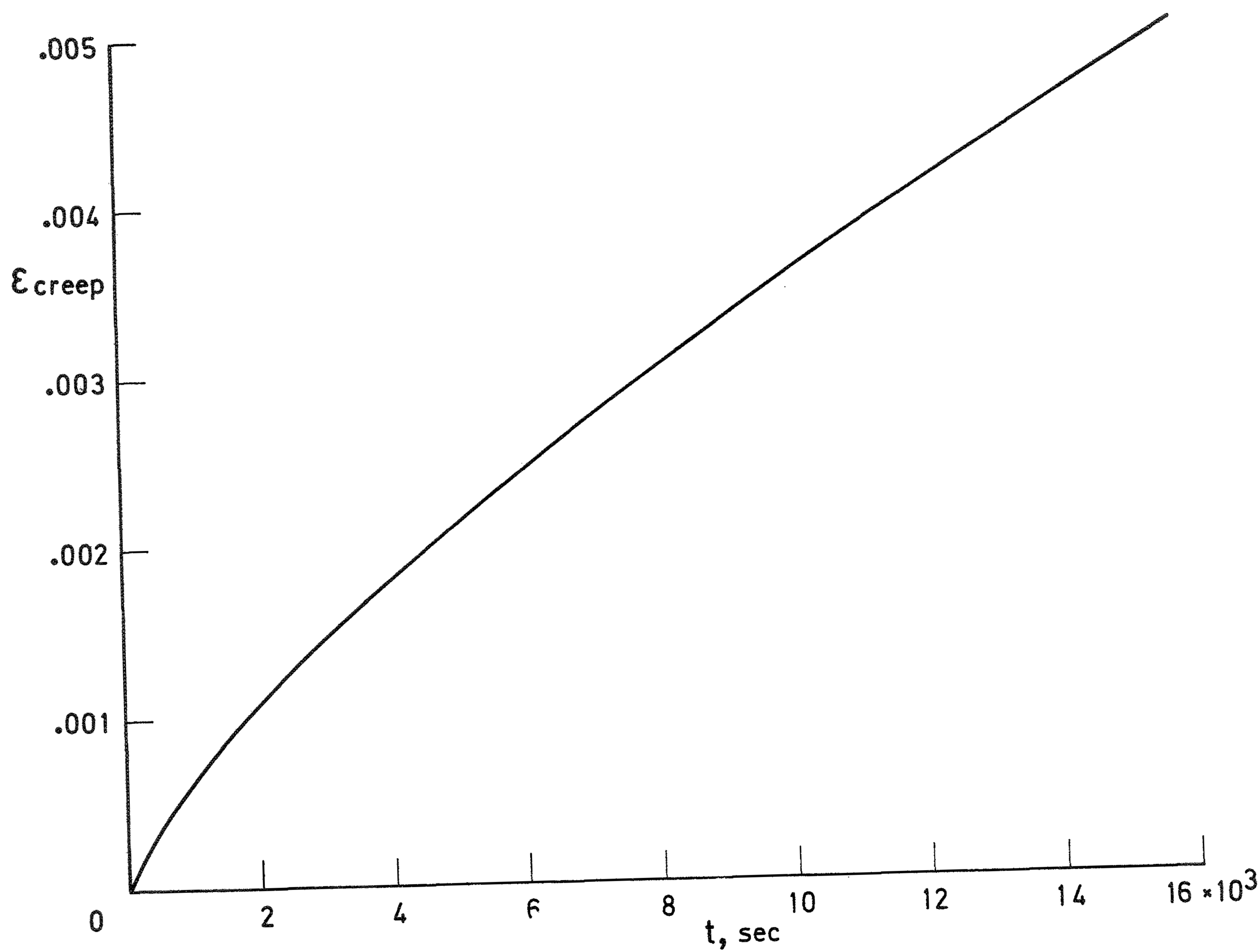


FIG. 5. TENSILE CREEP CURVE FOR AU-4GI ALUMINUM ALLOY AT 473°K, σ = 220MN/m²

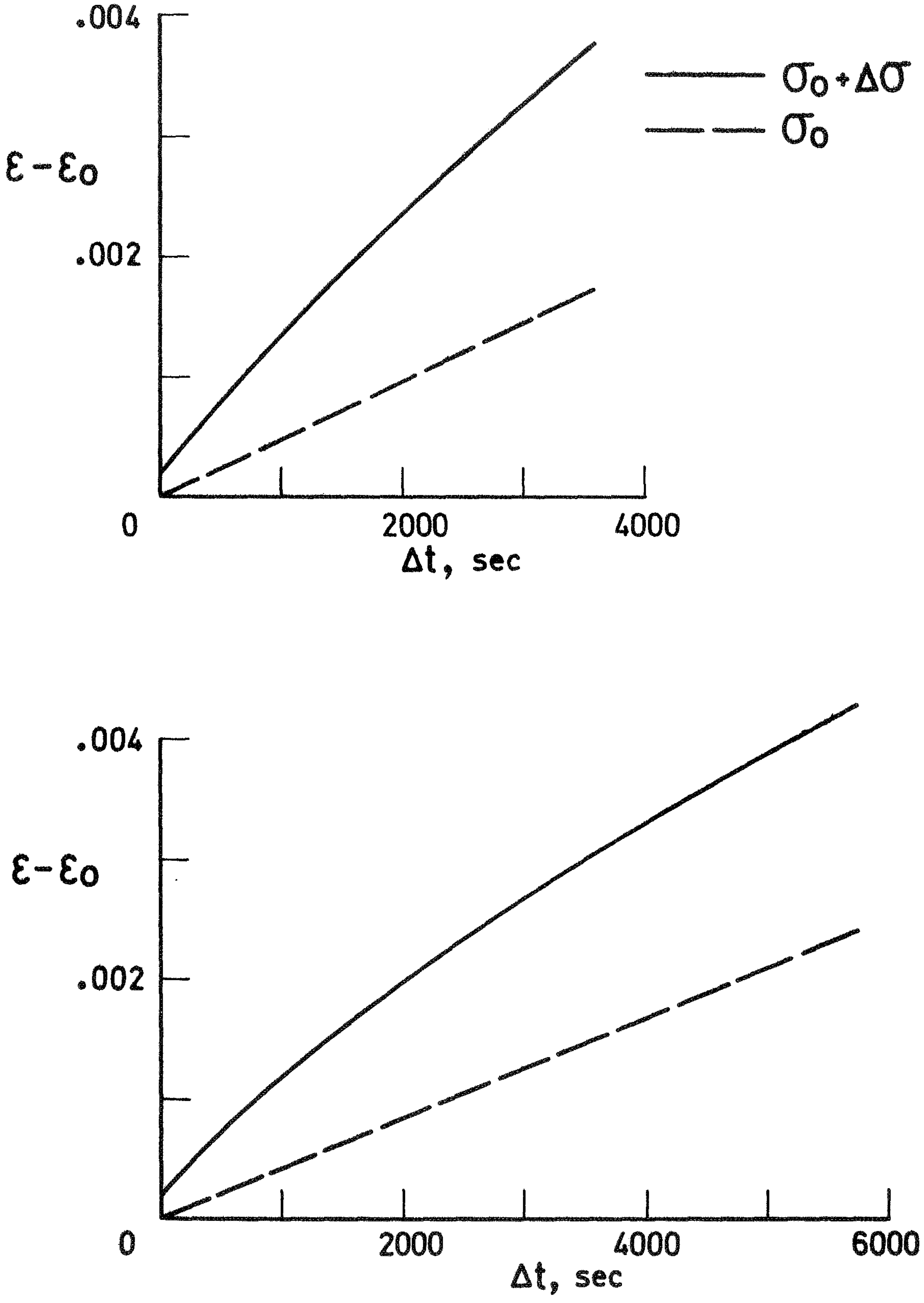
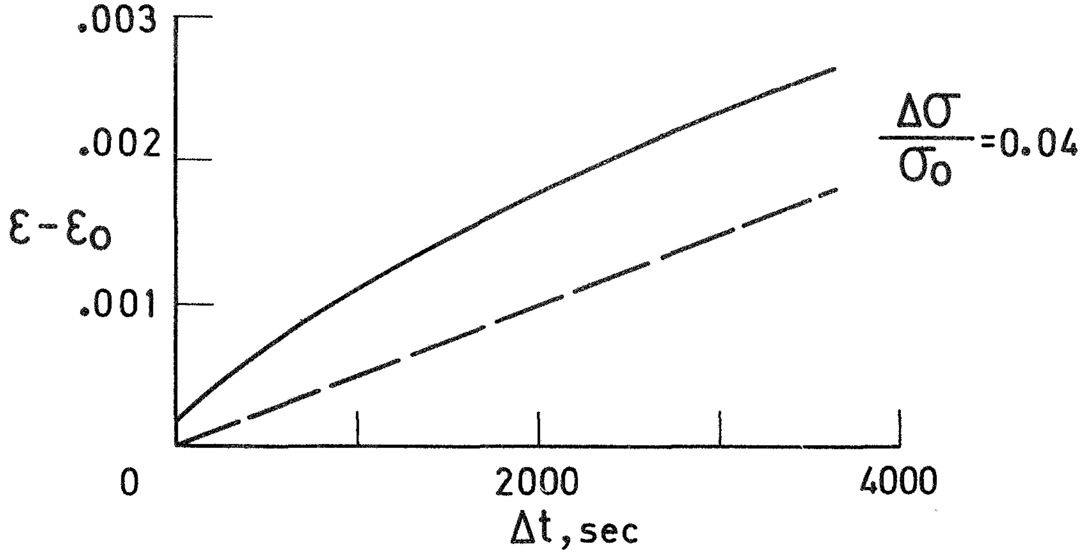
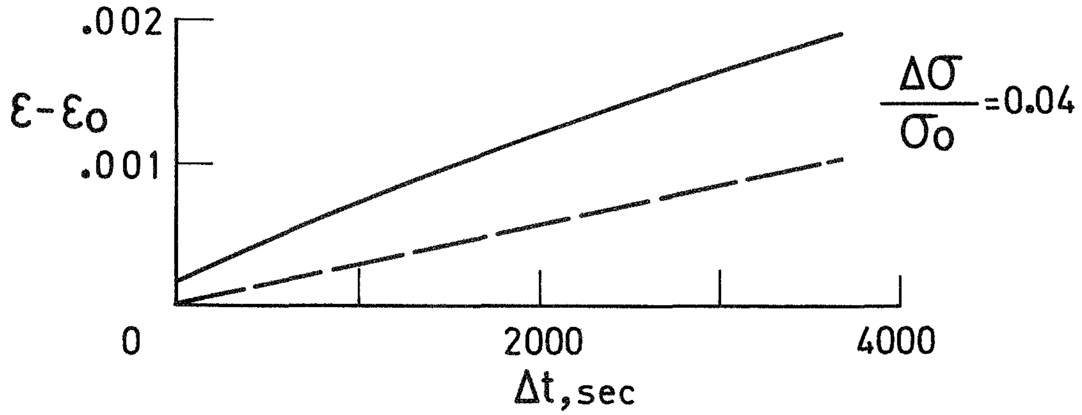


FIG. 6. STRAIN AFTER INCREASE IN STRESS DURING CREEP OF AU-4GI ALUMINUM ALLOY AT 473°K, $\Delta\sigma/\sigma_0 = 0.06$





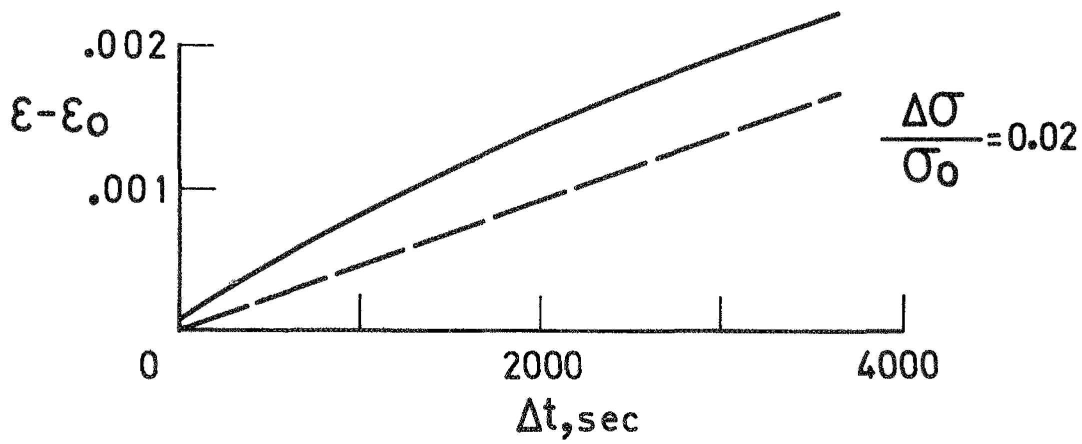


FIG. 7. STRAIN AFTER INCREASE IN STRESS DURING CREEP OF AU-4GI ALUMINUM ALLOY AT 473°K

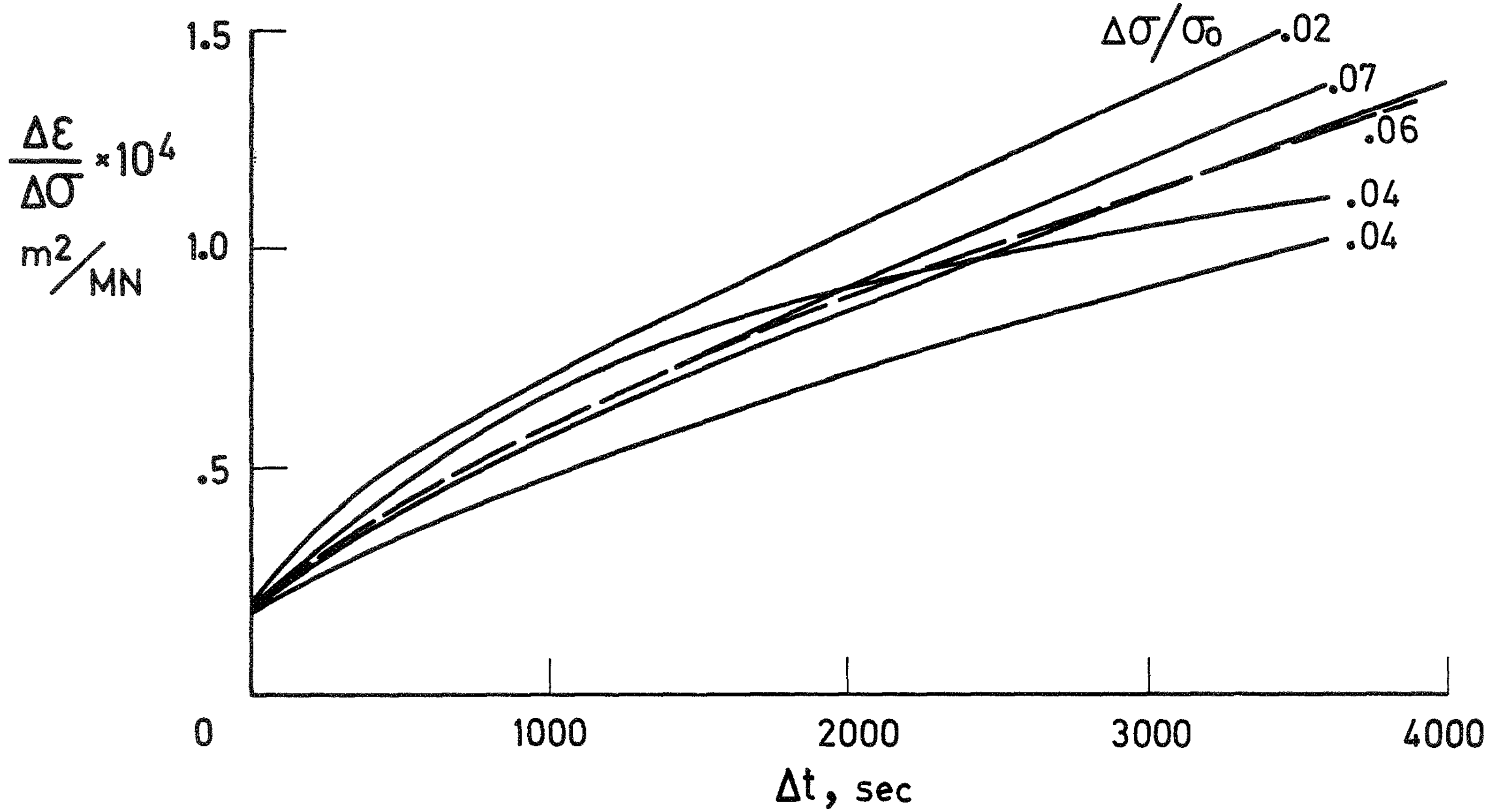


FIG. 8. STRAIN RESPONSE TO INCREASE IN STRESS FOR AU-4GI ALUMINUM ALLOY AT 473°K

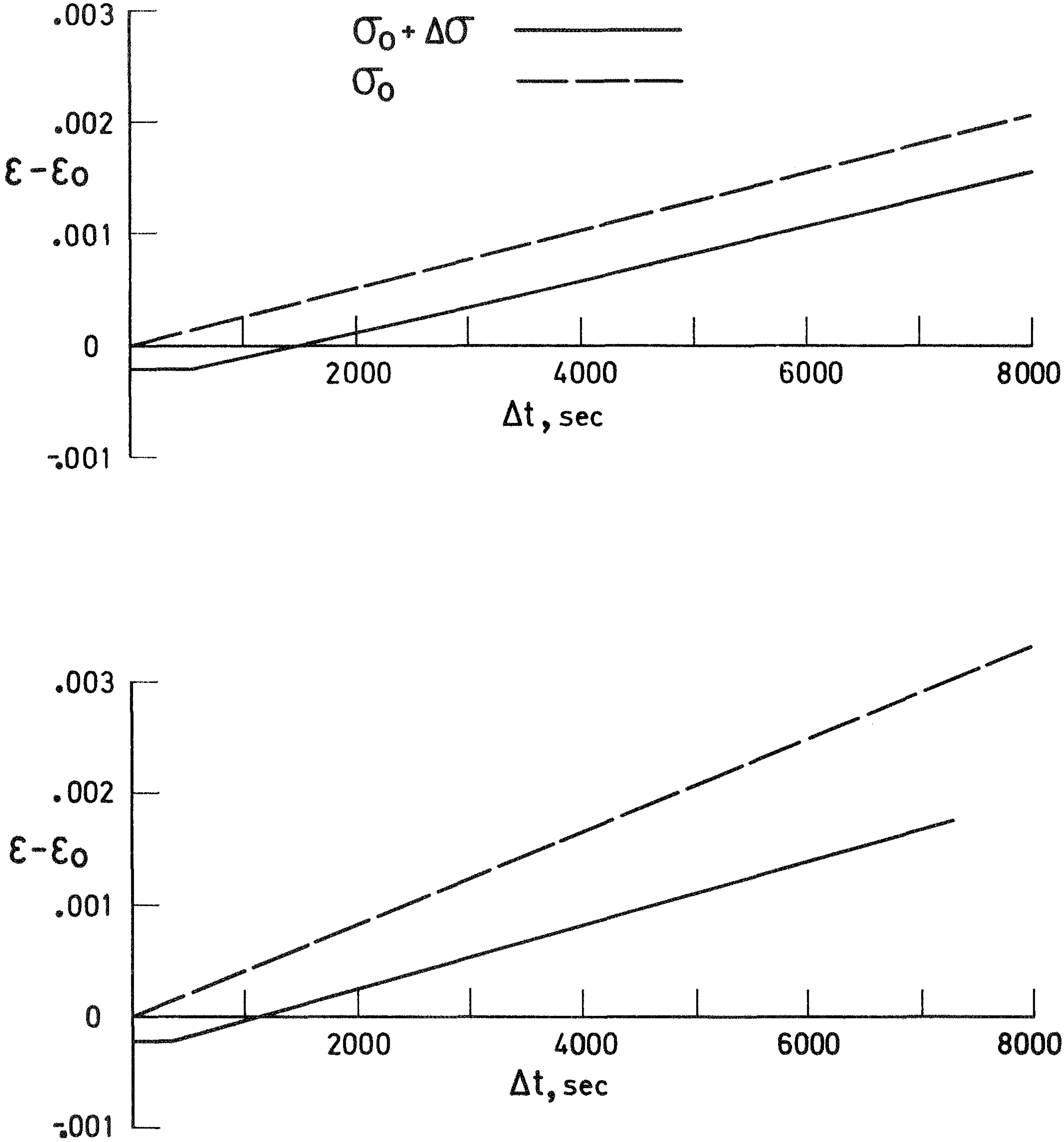


FIG. 9. STRAIN AFTER DECREASE IN STRESS DURING CREEP OF AU-4GI ALUMINUM ALLOY AT 473°K, $\Delta\sigma / \sigma_0 = -0.06$

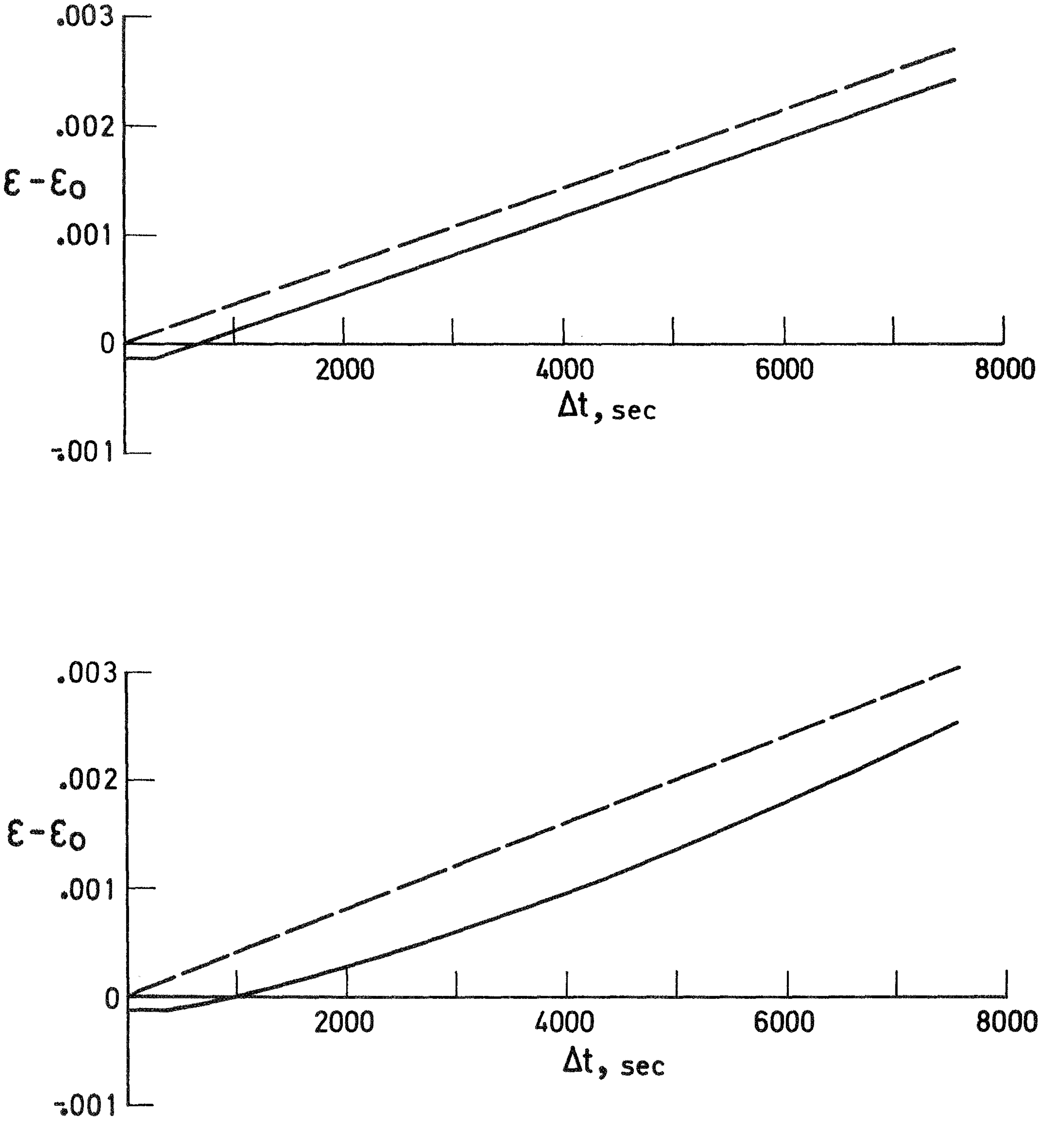
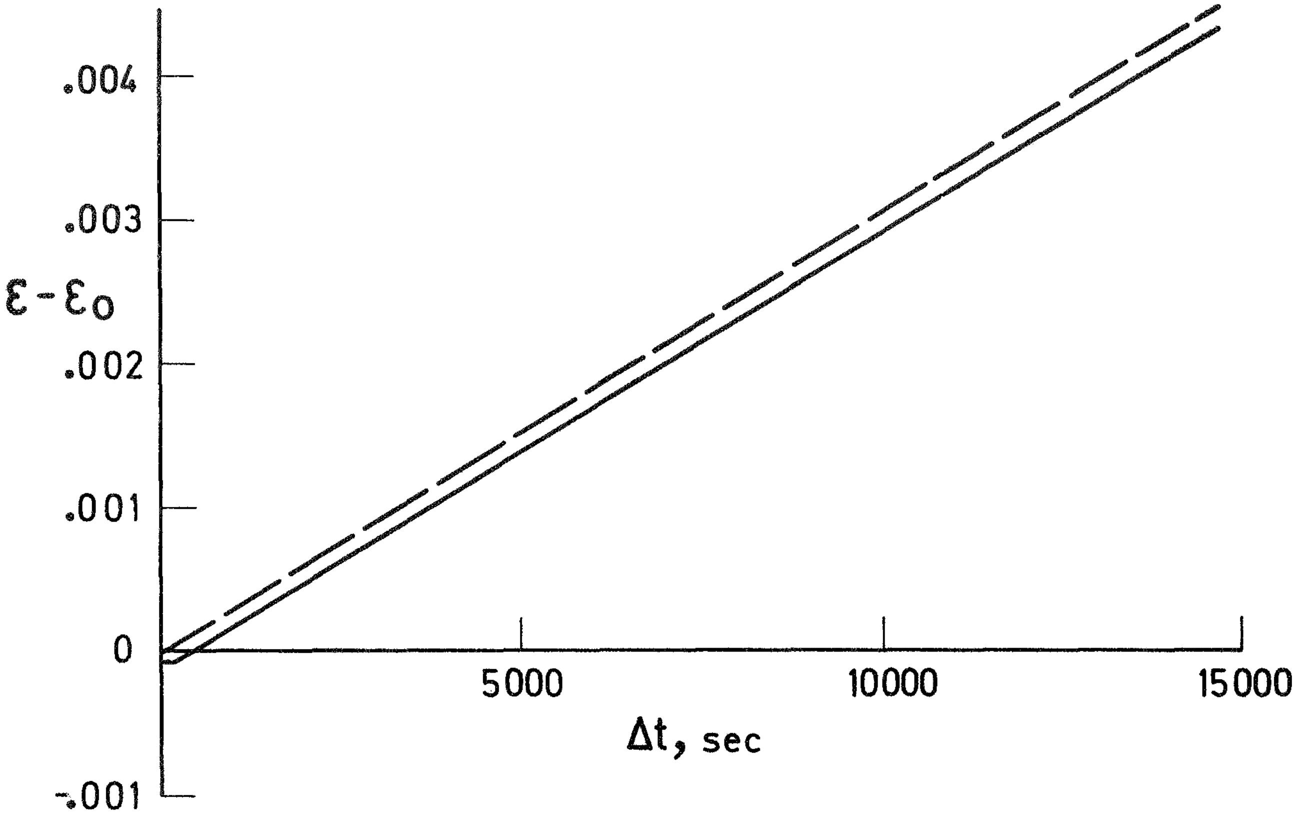


FIG. 10. STRAIN AFTER DECREASE IN STRESS DURING CREEP OF AU-4GI ALUMINUM ALLOY AT 473°K, $\Delta\sigma / \sigma_0 = -0.04$



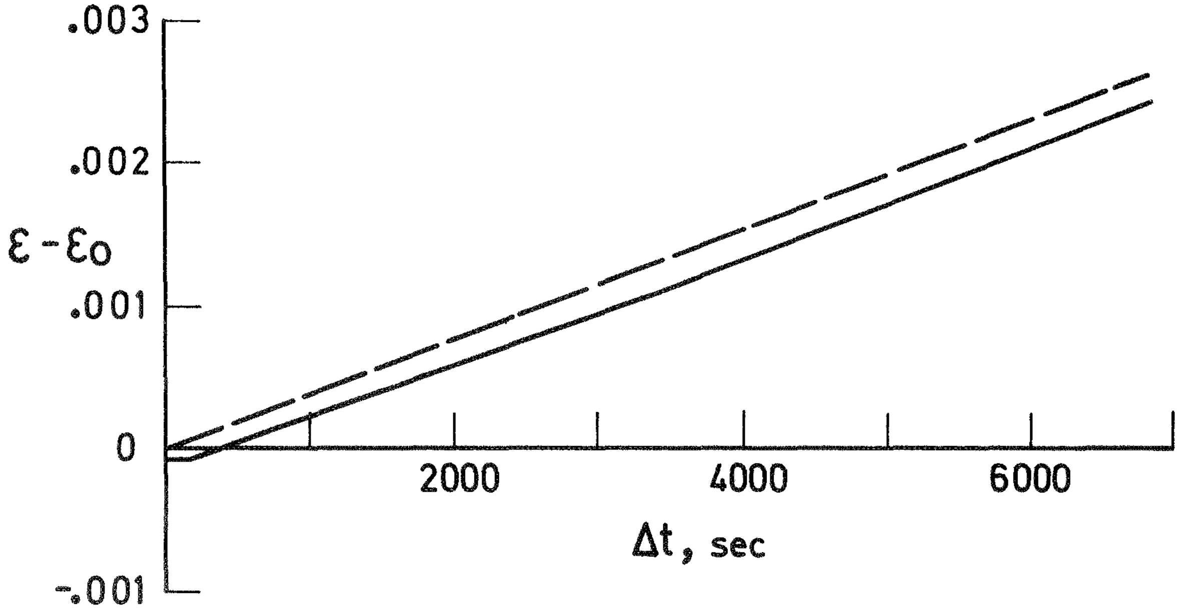


FIG. 11. STRAIN AFTER DECREASE IN STRESS DURING CREEP OF AU-4GI ALUMINUM ALLOY AT 473°K, $\Delta\sigma / \sigma_0 = -0.02$

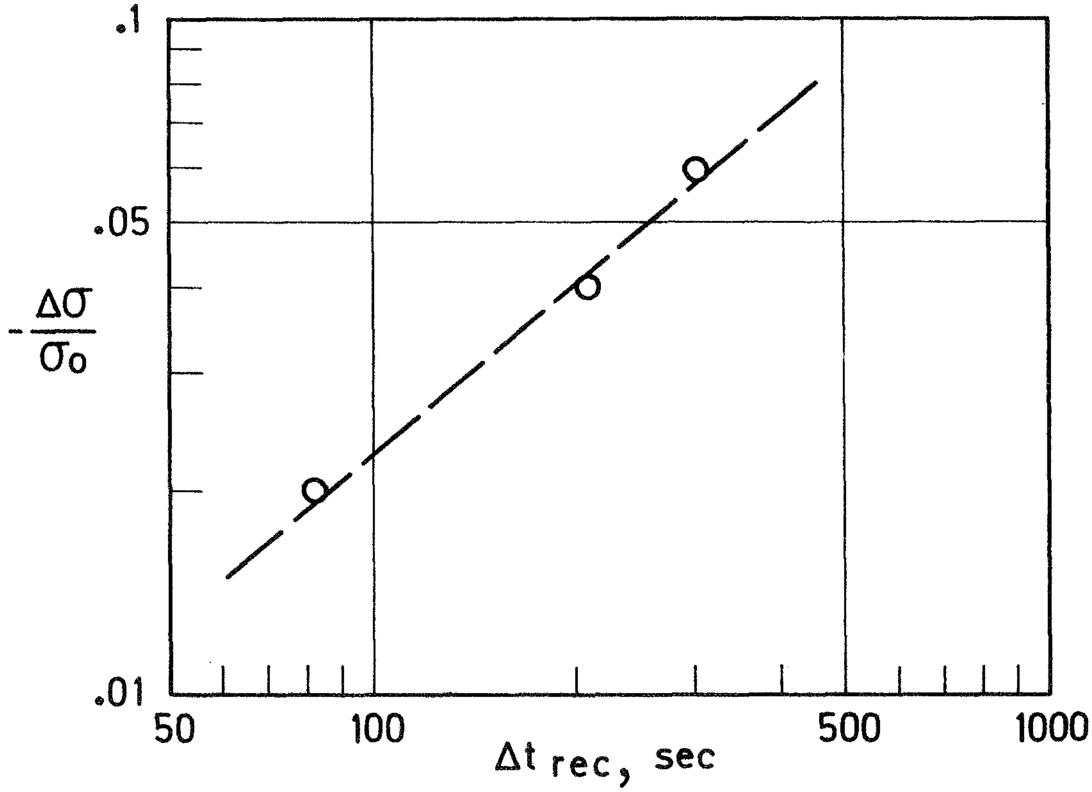


FIG. 12. AVERAGE INCUBATION TIME DUE TO STRESS DECREMENT AFTER 3 HR CREEP AT 473°K, AU-4GI ALUMINUM ALLOY