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Lawrence Radiation Laboratory
UNIVERSITY OF CALIFORNIA
LIVERMORE

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**EFFECTS OF TEMPERATURE, STRAIN, AND STRAIN RATE ON THE
MECHANICAL PROPERTIES OF PLUTONIUM-1 WT% GALLIUM
DELTA-STABILIZED ALLOYS**

Willis L. Barmore

Frank S. Uribe

June 22, 1970

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**EFFECTS OF TEMPERATURE, STRAIN, AND STRAIN RATE ON THE
MECHANICAL PROPERTIES OF PLUTONIUM-1 WT% GALLIUM
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**Willis L. Barmore and Frank S. Uribe
Lawrence Radiation Laboratory, University of California
Livermore, California 94550**

Various testing methods were used to obtain mechanical properties of Pu-1 wt% Ga δ -stabilized alloys. Stresses ranged from 250 to 20,000 psi, temperatures from 23 to 600°C, and strain rates from 10^{-5} to 10^{-1} sec⁻¹. Effects on mechanical properties of stress, temperature, and mechanical and thermal histories were studied. Strength properties obtained from compression, tension, shearing, and torsion tests were analyzed and compared, and the results are in close agreement. The flow stress increased with increasing strain rate and decreased with increasing temperature, indicating that one or more thermally activated deformation mechanisms control plastic deformation in this domain of testing.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

Introduction

As temperature is increased, plastic deformation of most crystalline solids occurs as a result of thermally activated motion of dislocations, grain boundary shearing, and stress-directed diffusion of vacancies(1). Such factors as modulus, diffusion coefficient, grain size, subgrain size, stacking fault energy, and dislocation density all are important parameters in the creep of metals and alloys(1,2). The apparent activation energies for creep are typically independent of creep strain, insensitive to the applied stress, and closely related to the activation energy for self-diffusion.

Deformation mechanisms involving dislocation motion and interaction frequently are dominant in the creep of many metals and alloys. Since dislocations possess great versatility and interact in many ways with each other and other lattice defects, numerous dislocation mechanisms can control plastic deformation at elevated temperature(1). Because of this and other considerations, little effort is made in this report to identify specific rate-controlling deformation mechanisms, but a general overall study is undertaken of important parameters which affect the strength of Pu-1 wt% Ga δ -stabilized alloys. A comprehensive paper on the effect of temperature on torsional strength and ductility of δ -stabilized Pu-Ga has been published by Wheeler and Robbins(3). They also reviewed prior investigations on the mechanical properties of δ -Pu alloys.

Gardner(4) reports that a flow stress in tension is strain-rate dependent but that no strain-rate effect on flow stress in compression was observed.

This investigation on the mechanical properties of Pu-1 wt% Ga δ -stabilized alloys was undertaken for the purpose of determining the effects of strain, strain rate, and temperature on the flow stress under compression, tension, and shearing. Results from various modes of testing on alloys of different minor impurity levels are compared. The flow stresses determined from the various test methods are essentially in agreement.

Materials

Three types of Pu-1 wt% Ga alloys were tested in this investigation, Table I. Type A material was made by melting and homogenizing buttons of unalloyed plutonium at 1000°C in a coated tantalum crucible and chill casting into a flat mold. A portion of this base material was in turn alloyed with gallium by arc melting to produce a master alloy of Pu-11 wt% Ga. The base material and the master alloy were combined by induction melting in a coated tantalum crucible and were subsequently cast into cooler Fibrefrax-coated cylindrical graphite molds ($T < 500^\circ\text{C}$) to minimize segregation. All these operations were done in a vacuum at less than $1 \mu\text{ Hg}$.

Type B and C materials were induction melted and alloyed in CaF_2 -coated tantalum crucibles in a vacuum ($1 \mu\text{ Hg}$) at 900°C or above. Alloys were cast into coated graphite molds 1 in. in diam preheated to 700°C . These rods were subsequently swaged to 1/2-in. diam. All types of alloys were homogenized at 460°C for 24 hr.

Metallographic specimens were prepared by conventional polishing techniques and then electro-etched at 3.5 V for 3 min in a solution of H_3PO_4 /ethyleneglycol/

Table I. Spectrographic Analysis of Pu-1 wt% Ga Alloys

Element	Composition, ppm		
	Type A ^a	Type B ^b	Type C ^c
Ag	<0.5	<0.05	<0.5
Al	<0.5	300	30
As	—	2	—
B	<0.5	<0.05	1
Be	<0.5	<0.05	<0.5
Bi	—	<0.1	—
Ca	<50	<1	<50
Cd	<10	<0.1	<10
Ce	—	—	—
Cr	<20	9	<20
Cu	<3	<0.05	10
Fe	<20	280	125
K	—	<0.1	—
Li	—	<0.05	—
Mg	<5	<1	<5
Mn	<3	<1	4
Mo	—	75	—
Na	—	<0.1	—
Ni	<20	<0.5	25
P	—	<10	—
Pb	<1	<1	<1
Si	<10	170	115
Sn	<10	0.1	<10
Ti	—	30	—
V	<25	2	<25
Zn	<10	<0.5	10
Co	—	<0.05	—
Ta	—	<10	—

^aHigh-purity alloy.

^bBattelle-Northwest.

^cNominal-purity alloy.

ethanol (8/5/5) followed by a 1-min etch at 9 V in a solution containing 28 g citric acid, 50 ml ethanol, and 1.5 ml 2.5N KNO₃.

A microstructure typical of annealed homogeneous material is shown in Figure 1-a. All the alloy types had grain sizes typically 50 μ in diam. Figure 1-b shows a microstructure that results from high-temperature deformation ($\epsilon \approx 0.2$, $T = 400^\circ\text{C}$).

Cylindrical rods were rolled into flat stock, and compression specimens with nominal dimensions of 0.2 X 0.2 X 0.5 in. were machined and annealed before testing. Dumbbell-shaped tensile specimens (0.2-in. diam, 0.5-in. gage length) were

turned on a lathe. The shear specimens were cylinders 1/4 in. in diam and 1 in. long, with a gage length of 0.050 in. In the standard annealing procedure, cold-worked specimens were heated to 460°C for 1 hr in high-purity argon.

Results and Discussion

All tests above room temperature were conducted in a nichrome resistance-wound clam-shell furnace controlled by a recorder-controller, in conjunction with an SCR power supply. During testing, specimen temperature was obtained from a chromel-alumel thermocouple and controlled to $\pm 5^\circ\text{C}$ in a test atmosphere of high-purity argon (< 10 ppm impurities). Loads were applied and controlled by an Instron testing machine.

A series of compressive stress-strain curves show the effect of temperature and strain on flow stress for a strain rate of $2 \times 10^{-2} \text{ sec}^{-1}$ (see Figure 2). Each curve can be expressed by an equation of the type $\sigma = \sigma_0 + K \epsilon^\beta$, where σ_0 is the initial flow stress, K is a scaling constant, and β is a constant characterizing the effect of strain hardening at a given temperature. As temperature is increased, the rate of work hardening decreases because recovery processes become predominant at higher temperatures. Plutonium-1 wt% gallium delta-stabilized alloys can be strain hardened to require flow stresses greater than 30,000 psi at room temperature, but an apparent limit to strain hardening occurs before flow stress of 40,000 psi are reached.

The following equation has been used traditionally to analyze the creep of metals and alloys at elevated temperatures:

$$\dot{\epsilon} = K f(S) \sigma^n e^{-\frac{\Delta H}{RT}},$$

where $\dot{\epsilon}$ = creep rate, K = constant, σ = stress, ΔH = apparent activation energy for creep, R = gas constant, T = temperature in $^\circ\text{K}$, n = stress exponent, and $f(S)$ = micro-structure function.

At constant temperature, the effect of stress on creep is of the form $\dot{\epsilon} = C\sigma^n$, which is frequently called a "stress law." Stress laws at various temperatures are displayed in Figure 3. Included in this figure are data from compression, tension, and shear tests, where a strain rate is imposed on a specimen and the resultant stress determined. Results from torsion are also shown. As evident, equivalent values of flow stress are obtained and closely correlated. At all temperatures, the shear stress (τ) was multiplied by two to give an effective axial stress because the ratio of σ to τ was two at room temperature, and shear strain (γ) was divided by two to give the axial strain rate. This demonstrates the close relationship between the flow stresses measured by the various testing modes and suggests that the deformation mechanism is probably the same for each testing method.

The temperature effect on flow stress for constant strain rate is shown in Figure 4. The stress exponent (n) diminishes markedly with increasing temperature with a corresponding decrease in creep rate sensitivity to the applied stress (see Figure 5).

The temperature effect on creep rate for various compressive stress levels is given in Figure 6. The average apparent activation energy for creep is 46 kcal/mole. Lytton et al.(5) obtained a value of 43.6 kcal/mole for compressive creep on delta-stabilized 1 wt% Ga alloys of similar composition to those studied in this investigation. Barrett et al.(6) proposed a method for calculating the activation energy for self-diffusion using an equation of the following type:

$$\Delta H_{sd} = \Delta H_c + nR \frac{T^2}{E} \frac{dE}{dT},$$

where ΔH_{sd} = activation energy for self-diffusion, ΔH_c = apparent activation energy for creep, E = the elastic modulus at temperature, and n = the stress exponent. A ΔH_{sd} of 38 kcal/mole is calculated using this relation, which is in good agreement with the ΔH_{sd} of 36.3 kcal/mole measured by Wade(7).

When $\dot{\epsilon}/D$ is plotted vs σ/E on a logarithmic scale (Figure 7), as suggested by Sherby and Burke(2), most of the data from Figure 4 scatter closely about a straight line with a slope of about 7.4.

The result is a general equation that describes the strain rate-flow stress relation of the type $\dot{\epsilon}/D = K(\sigma/E)^{7.4}$. Expressions of this type can be used to describe the elevated temperature deformation behavior of many metals and alloys. This expression gives a power stress law at low stresses. This procedure further demonstrates the intimate relationship between creep and self-diffusion.

Conclusions

- As temperature is increased, the work hardening rate decreases.
- The stress exponent (n) is the same value at a given temperature for compression, tension, and shearing deformation. Effective flow stresses are in close agreement, suggesting that the same process controls plastic deformation in compression, tension, shearing and torsion testing.
- The stress exponent decreases from ~ 100 at 23°C to about 1.5 at 600°C, showing the increased sensitivity of stress to deformation rate at higher temperatures.
- Flow stress decreases with increasing temperature and increases with increasing strain rate, indicating that thermally activated rate-controlling deformation processes are operative.
- The average activation energy (ΔH) for creep is 46 kcal/mole, is insensitive to stress, and can be correlated with the activation energy of self-diffusion in plutonium-1 wt% gallium delta-stabilized alloy.
- The plastic deformation behavior of this alloy can be described by the relation $\dot{\epsilon}/D = K(\sigma/E)^{7.4}$, demonstrating the close relationship between creep and self-diffusion.

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a

b

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Barmore - Fig. 2

Barmore - Fig. 3

Barmore - Fig. 4

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Barmore - Fig. 7