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AEC Research and Development Report

THE EFFECT
OF STRAIN RATE AND TEMPERATURE
ON THE TENSILE PROPERTIES
OF Pu-1 WT% Ga ALLOYS

3 3679 00061 7888

BNWL-1567
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Metals, Ceramics,
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OF Pu-1 WT% Ga ALLOYS

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August 1971

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M. D. Merz

SUMMARY

The tensile properties of a plutonium-1 wt% gallium alloy (fcc, delta stabilized) with two iron levels were determined at strain rates from 3.3×10^{-4} to 20 sec^{-1} and temperatures from 25 to 500°C . The yield stress and ultimate tensile strength increased with strain rate in proportion to $\log \dot{\epsilon}$ at 25 and 100°C . At an intermediate temperature range, 150 to 200°C , the yield stress and ultimate strength were relatively insensitive to strain rate. At 300 and 500°C , both properties increased with strain rate at strain rates higher than 0.1 sec^{-1} . At 400°C , Pu-Pu₆Fe melting occurred in the alloy containing 235 ppm iron. No melting occurred in the alloy containing 100 ppm iron. Pu-Pu₆Fe melting caused embrittlement at 400°C at all testing rates.

The ultimate tensile strength was relatively insensitive to strain rate at 400°C increasing from 4800 psi at 0.01 sec^{-1} to 6600 psi at 18 sec^{-1} . Total elongation and reduction in area did not change significantly with strain rate at a given temperature. However, as the test temperature was increased at a given rate, the elongation and reduction in area exhibited minima in the temperature interval of 100 to 200°C , increased at 300°C , and decreased to very low values at 400°C due to Pu-Pu₆Fe melting. Recrystallization occurred during the tests at 400 and 500°C .

INTRODUCTION

The tensile properties of a delta stabilized Pu-1 wt% Ga alloy were determined at strain rates of 0.01, 0.15 and 18 sec^{-1} at temperatures from 23 to 500°C . An earlier study revealed very little strain rate sensitivity

in similar alloys over a smaller range of rates; the present work was done to explore the effects at higher rates and to investigate embrittlement due to Pu-Pu₆Fe eutectic melting at higher rates.

EXPERIMENTAL PROCEDURE

The plutonium alloy used in this investigation contained 1.0 wt% gallium and approximately 235 ppm iron with no other impurities in excess of 50 ppm by weight. The alloy was rolled at 23°C from 0.100 to 0.075 inch thickness and annealed 18 minutes at 265°C and had a density of 15.75 gm/cm³. The microstructure after this treatment consisted of core regions elongated by rolling (Figure 1). The tensile specimens were machined on a Tensikut machine with gage length of 1 inch × 1/4 inch wide. The surface was lightly sanded on 4/0 paper prior to testing to remove oxide and small surface blemishes due to rolling.

The results of tests on cast and homogenized Pu-1 wt% Ga alloys are also included in this report.⁽¹⁾ These specimens were not deformed prior to testing and were therefore of lower strength than the sheet specimens. These test samples were round 0.252 inch diameter tensile rods with gage lengths of 1 inch. These samples were homogenized for 20 hours at 450°C after the casting and machining. This alloy contained 100 ppm iron impurity.

The tests on the sheet specimens were done on a gas-driven machine similar to that described by Krafft.⁽²⁾ The speed of testing was controlled by either changing the gas pressure or reducing the size of the orifice through which the coupling oil passed. Rates were determined by measurement with a dial indicator at the two slower speeds (0.01 and 0.15 sec⁻¹) and by the elastic loading rate for the highest speed (18 sec⁻¹). The slower tests at strain rates 0.00033, 0.0033 and 0.033 sec⁻¹ on the cast and homogenized specimens were done on an Instron machine.

A load cell was placed directly above the specimen grip on the Krafft machine. The output from the four bonded gages comprising the cell was

(a)

(b)

FIGURE 1. Microstructure of Warm-Worked Pu-1 wt% Ga Showing Cored Regions Elongated by Rolling: (a) as polished, dark areas are gallium rich; (b) electro-polished and etched showing grain structure (500X).

measured on an oscilloscope using a Polaroid camera for the testing speeds of 18 sec^{-1} and 0.15 sec^{-1} . At the slowest rate (0.01 sec^{-1}) an x-y recorder was used to record the load.

Considerable difficulty with load cell ringing was encountered at the rate of 18 sec^{-1} . The load oscillations were appreciable and a dummy specimen of aluminum was instrumented with gages to determine the relation of load cell output to stress in the specimen. The signal from the specimen indicated no oscillation in the specimen during elastic loading. The mean value of the signal from the load cell corresponded to the load existing in the specimen. Consequently the mean value of the oscillating signal from the load cell was used as the stress-determining load for this specimen. In several of the tests at the higher temperatures, the magnitude of oscillations was too large relative to the load value to make a meaningful stress determination. Only the elongation and reduction in area were determined for these cases.

The specimens were held at the testing temperature using a clam-shell quartz lamp radiant furnace. The control thermocouple was placed within the grip near the specimen shoulder; the measurement thermocouple was placed directly in contact with the specimen gage length and was shielded from the quartz lamps. The temperature was maintained to within $\pm 2^\circ\text{C}$.

The problem of adiabatic heating must be considered, especially for the tests at high rates where heat generated by straining cannot be dissipated during the test. Assuming no heat lost, the temperature rise is

$$\Delta T = \frac{\bar{V}}{C_v} \int_0^{\epsilon_f} \sigma d\epsilon - \dot{T} t$$

where C_v is constant volume heat capacity, $\bar{V}$ is the molar volume, σ is the stress, ϵ_f is the fracture strain, T is the natural cooling rate of the specimen with no heat input, and $\dot{T}$ equals approximately $3.3^\circ\text{C}/\text{sec}$ as determined by holding the specimen at a fixed temperature and then turning off the furnace power and noting the temperature decay. Based on the results in Table 2, maximum temperature rises in the necked region of this specimen were calculated and are given in Table 1.

TABLE 1. Calculated Temperature Rise in Specimens Tested at Various Rates

Test Temperature	Temperature Rise		
	$\dot{\epsilon} = 0.01 \text{ sec}^{-1}$	$\dot{\epsilon} = 0.15 \text{ sec}^{-1}$	$\dot{\epsilon} = 18 \text{ sec}^{-1}$
25°C	nil	82°C	94°C
300°C	nil	39°C	54°C
400°C	nil	nil	1°C

The temperature rise is greatest at the high rates and low temperatures because the stress is highest there and little time is available for dissipation of heat.

RESULTS

The tensile properties are summarized in Table 2. The yield strength and ultimate tensile strength decreased with increasing temperature (Figure 2). The elongation exhibited a more complex variation (Figure 3). There was minimum between 100 and 150°C with maximum elongations and reduction in area (R.A.) between 300 and 400°C. At 400°C the elongations and reductions in area were very low.

The effect of strain rate on the yield strength and tensile strength depended on the testing temperature (Figures 4 and 5). At 25 and 100°C there was a linear increase in strength with the logarithm of strain rate. At 200°C the strength was relative insensitive to changes in rate for the range tested. At 300 and 400°C, the strengths increased with strain rate above 0.15 sec^{-1} .

The appearance of the tensile specimens reflected the changes in elongation and reduction in area (Figure 6). Metallographic examination of these specimens revealed that Pu-Pu₆Fe eutectic melting and grain boundary embrittlement occurred in those specimen with low elongation and R.A. at 400°C (Figure 7). The melting was attributed to the presence of Fe impurities. Several investigators^(3,4) have observed embrittlement around 400°C and have attributed this to Pu-Pu₆Fe melting due to iron

impurities. Embrittlement is reported to occur above levels of about 200 ppm by weight and at temperatures as low as 375°C in Pu-1 wt% Ga alloys.⁽⁴⁾ The embrittlement occurred at all rates in the present study and was not suppressed by testing at the highest rate of 18 sec⁻¹.

TABLE 2. Tensile Properties of Pu-1 wt% Ga Alloy

a. Strain Rate = 18 sec⁻¹

Test Temperature, °C	Yield Strength, psi	Ultimate Strength, psi	Elongation, %	R.A. [†] %
25	24,000	25,600	21	61
25	27,900	30,700	23	44
25	27,000	31,500	21	46
100	25,200	27,300	14	37
100	*	*	15	40
200	16,500	*	8	56
200	14,800	17,600	14	45
300	12,800	13,500	14	67
300	14,800	14,800	17	48
400	*	*	3	11
400	*	6,600	1.2	3.8

b. Strain Rate = 0.15 sec⁻¹

25	22,900	24,800	15	60
100	18,700	21,000	15	50
200	15,300	16,000	11	59
300	*	7,910	19	87
400	*	4,280	<1	3

c. Strain Rate = 0.01 sec⁻¹

25	20,000	23,600	16	60
100	17,500	19,200	11	59
200	15,500	16,900	12	60
300	7,500	8,100	19	100
400	4,300	4,840	26	84
425	*	1,500	<1	3

*Indicates stress undetermined

†Reduction in area

FIGURE 2. Yield Stress and Ultimate Tensile Strength of Warm-Worked Pu-1 wt% Ga Alloy Versus Testing Temperature for Three Rates.

FIGURE 3. Elongation of Warm-Worked Pu-1 wt% Ga Alloy Versus Testing Temperature.

(c)

FIGURE 3. (Continued)

FIGURE 4. Yield Stress of Warm-Worked Pu-1 wt% Ga Alloy Versus Strain Rate for Different Test Temperatures.

FIGURE 5. Ultimate Tensile Strength of Warm-Worked Pu-1 wt% Ga Alloy Versus Strain Rate for Different Test Temperatures.

6 a

6 b

6 c

FIGURE 6. Tensile Specimens of Warm-Worked Pu-1 wt% Ga Alloy for Different Testing Rates and Temperatures.

FIGURE 7. Microstructure of Warm-Worked Pu-1 wt% Ga Alloy After Testing at 400°C at 18 sec⁻¹ Showing Cracking Caused by Pu-Pu₆Fe Melting, 250X.

The test results on the cast and homogenized alloy (no prior deformation by rolling) are summarized in Table 3.⁽¹⁾ The yield and ultimate tensile strengths showed trends similar to that for the warm-worked alloy (Figures 8 and 9). There was, however, no indication of embrittlement in this alloy (Figure 10).

TABLE 3. Tensile Properties of Pu-1 wt% Ga Alloy Cast and Homogenized for 20 hour at 450°C

a. Strain Rate = 20 sec ⁻¹				
Test Temperature, °C	Yield Strength, psi	Ultimate Strength, psi	Elongation, %	R.A. %
25	20,400	28,700	31	56
25	21,700	27,200	42	57
150	9,300	12,800	37	68
150	11,240	14,760	39	81
300	9,780	13,400	50	75
300	8,720	12,700	28	75
400	7,560	8,940	50	90
400	>3,440	>7,480	44	94
b. Strain Rate = 2.2 to 3.5 sec ⁻¹				
25 (2.6 sec ⁻¹)	18,400	26,400	41	54
150 (2.7 sec ⁻¹)	10,000	10,200	28	81
150 (3.5 sec ⁻¹)	10,900	14,900	--	--
150 (2.3 sec ⁻¹)	9,410	>11,800	38	75
150 (2.2 sec ⁻¹)	10,100	14,100	38	81
300 (2.4 sec ⁻¹)	9,420	12,500	42	75
400 (3.0 sec ⁻¹)	5,420	5,880	61	99
500 (2.9 sec ⁻¹)	6,840	7,580	54	--
c. Strain Rate = 0.33 sec ⁻¹				
150	13,600	13,600	35	90
400	3,440	3,440	40	99
d. Strain Rate = 0.033 sec ⁻¹				
25	16,700	24,200	41	60
150	10,600	14,200	34	81
400	2,730	2,690	56	95
400	3,180	3,180	75	97
500	1,690	1,690	23	44

TABLE 3. (Continued)

Test Temperature, °C	Yield Strength, psi	Ultimate Strength, psi	Elongation, %	R.A. %
e. Strain Rate = 0.0033 sec^{-1}				
25	10,400	15,400	33	75
150	7,840	11,100	39	81
150	8,640	13,240	31	75
150	8,700	12,270	31	80
300	4,420	5,260	50	99
400	2,690	2,890	67	99
500	1,270	1,310	--	99
500	1,470	1,470	88	99
f. Strain Rate = 0.00033 sec^{-1}				
25	12,500	19,600	45	54
150	7,960	13,600	31	78
150	8,150	12,700	31	78
150	8,790	13,300	31	81
300	4,560	4,730	41	86
400	2,560	3,240	50	97
475	<370	370	--	--

FIGURE 8. Yield Stress of Cast and Homogenized Pu-1 wt% Ga Alloy Versus Strain Rate for Different Temperatures.

FIGURE 9. Ultimate Tensile Strength of Cast and Homogenized Pu-1 wt% Ga Alloy Versus Strain Rate for Different Temperatures.

FIGURE 10. Elongation of Cast and Homogenized Pu-1 wt% Ga Alloy Versus Test Temperature.

FIGURE 10. (Continued)

FIGURE 10. (Continued)

DISCUSSION

The tests were made at temperatures ranging from 0.35 to $0.80 T_m$ (25 to 400°C) and it is therefore appropriate to compare the observed behavior to that of other fcc metals at corresponding homologous temperatures. The yield strength and ultimate tensile strength increased by a factor of about 1.3 at 25 and 100°C when the strain rate was increased from 10^{-2} sec^{-1} to 18 sec^{-1} . This can be compared to the behavior of 1060-0 and 1100-0 aluminum at room temperature ($0.32 T_m$) which exhibits a smaller strain rate dependence over this range of strain rate^(5,6) (about 1.15 for stress at 50% strain and about 1.1 for the yield stress). These data are in the strain rate range where strength (measured either by yield offset, flow stress at a fixed strain or ultimate strength) is usually relatively insensitive to strain rate ($\dot{\epsilon}$ less than about 10^3 sec^{-1}). The relation $\sigma = k_1 + k_2 \log \dot{\epsilon}$ is typically obeyed in this region. This equation was valid for the yield stress of Pu-1 wt% Ga (Figure 4), with $k_2 = 2000$ and $k_2 = 24,000$ psi at 25°C and $k_1 = 22,000$ psi at 100°C .

The decrease in strain rate sensitivity at 150°C and 300°C was not expected and may be due to strain ageing effects. Wheeler and Robbins observed an anomaly in torsion testing of a similar alloy in the region of 100 to 200°C .⁽⁷⁾ A sharp increase in the number of twists to failure was observed between 150°C and 200°C ($\dot{\epsilon} \approx 0.024 \text{ sec}^{-1}$). This was related to the occurrence of local regions of high shear strain in the specimens tested below the transition. Such local deformation is characteristic of strain ageing and occurs more extensively in torsion because of the lack of dimensional constraints. Gardner observed that the hardness of Pu-1 wt% Ga increased upon holding at 200°C , again suggesting that an ageing reaction takes place at this temperature.⁽³⁾ The minimum in ductility in the temperature range of 100 to 200°C can be reasonably attributed to strain ageing, similar to that observed in mild steel at 200°C and α brass.

The increase in elongation between 200 and 300°C was probably due to recovery associated with the onset of recrystallization. The metal tested

at 200°C retained the elongated grains caused by rolling; that tested at 300°C had more clearly delineated grain boundaries though they were still elongated; and the metal tested at 400°C was definitely recrystallized with almost equiaxed grains (Figure 7). The fact that the strength of the rolled sheet at 400°C was still higher than that of the cast and homogenized alloy (compare Table 1 and Table 2) was further evidence that recrystallization was not complete, even at 400°C.

The embrittlement due to Pu-Pu₆Fe melting was not suppressed by increasing the strain rate to 18 sec⁻¹. Because the strength remained reasonably high under conditions where melting occurred, it is thought the strength was determined by the strength of those areas which contained no Pu-Pu₆Fe phase and were able to carry a load. Embrittlement accompanying Pu-Pu₆Fe eutectic melting in delta plutonium has been studied in some detail by others but whether true liquid metal embrittlement (reduction of fracture surface energy) occurs in these alloys has not been determined and remains as a question to be answered by more detailed study of the fracture process.

CONCLUSIONS

- The yield stress and ultimate tensile strength of Pu-1 wt% Ga increased proportional to $\log(\dot{\epsilon})$ at 25 and 100°C.
- The yield stress and ultimate tensile strength was relatively insensitive to strain rate at 150 and 200°C.
- At 300 and 500°C the yield stress and ultimate strength increased with increasing rate above about 0.1 sec⁻¹.
- At 400°C, Pu-Pu₆Fe melting occurred at all testing rates (0.01 to 20 sec⁻¹) and embrittlement occurred. The fracture stress was relatively insensitive to strain rate under these conditions, varying from 4800 to 6600 psi.
- The total elongation and reduction in area did not change significantly with strain rate at a given temperature. As the test temperature was increased at a particular rate the elongation and reduction in area

exhibited minimum in the temperature range 100 to 200°C, increased somewhat at higher temperatures and decreased to very low values when Pu-Pu₆Fe eutectic melting occurred at 400°C.

- Recrystallization occurred at testing temperatures of 400°C and higher.

ACKNOWLEDGEMENTS

The author thanks W. R. Boyer for doing the high rate testing and G. H. Giddings for the metallographic work and appreciated the helpful comments of R. D. Nelson and H. R. Gardner.

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ACKNOWLEDGMENTS

The author thanks M. R. Hays for doing the high rate testing and
 C. H. Dilling for the microphotographic work and assistance in the
 laboratory of R. E. Nelson and H. R. Hays.

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