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THE FATIGUE BEHAVIOR OF Pu-1.0 w/o Ga
DELTA STABILIZED PLUTONIUM

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DELTA STABILIZED PLUTONIUM

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Reactor and Materials Technology Department

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INTRODUCTION

In the Pu-1.0 w/o Ga alloy, mechanical properties are greatly affected by metallurgical condition. Yield strengths (.2%) range from 11,000 psi to 32,000 psi for cored as-cast and cored and 94% rolled alloy, respectively. In addition, rolling or compression in sufficient amounts causes alpha phase formation to occur in cored alloy which further influences properties. Because of concern over the influence of the wide variation obtainable in metallurgical condition on fatigue behavior, this study was initiated.

SUMMARY AND CONCLUSIONS

Several metallurgical conditions of Pu-1.0 w/o Ga alloy sheet were fatigue tested at room temperature in cyclic flexure with a superimposed mean stress. It was concluded that fatigue strength was relatively insensitive to yield strength, i.e., metallurgical condition. Over a 0.1% yield strength range of 10,300 to 30,400 psi, fatigue strength varied only from 10,000 to 15,000 psi. The cored, as-cast; and homogenized, 94% rolled, 300 C annealed conditions had the lowest fatigue strengths while the cored, 86% rolled sheet had the highest fatigue strength. The presence of alpha phase either initially or introduced during testing seems to impart increased resistance to fatigue failure.

PROCEDURE

Room temperature fatigue testing was done in the mean stress testing apparatus previously used for unalloyed plutonium.⁽¹⁾ Briefly, the fatigue specimen is vibrated in flexure by air pressure similar to a reed in the harmonica. The resultant stress cycle ranged from $\sigma_c + \sigma_m$ to $\sigma_c - \sigma_m$ where σ_c is the cyclic stress and σ_m is a mean stress. The cyclic stress was determined from the following relation.⁽²⁾

$$\sigma_c = \frac{hE}{2(1 - \nu^2)} \frac{(\cos rl + \cosh rl)}{(\sin rl \sinh rl)} r^2 X,$$

where h = thickness of fatigue specimens,
0.050 in.,

E = modulus of elasticity,

ν = Poisson's ratio,

rl = 1.875 radians,
 l = free length of specimen,
1.57 in.,
 X = one-half amplitude of
vibration.

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The mean stress was determined from the equation for a uniformly loaded cantilever beam:

$$\sigma_m = \frac{2 h E X_0}{(1-\nu^2) l^2},$$

where X_0 is the constant deflection from horizontal of the free end of the specimen during vibration. The specimen is nominally 0.050 inches thick, 0.625 inches wide with a constant cross section, free length of 1.57 inches. Unless specified otherwise, all specimens were taken with their longitudinal axis of symmetry parallel to the rolling direction.

Fatigue failure was taken at the point on the vibration frequency-time curve where the frequency had decreased 0.4%, i.e., one cycle/second. Here, although failure had started, no visible crack could be detected when the specimens were forced to fracture by mechanical bending. Specimens allowed to vibrate until they stopped, exhibited typical fatigue fractures. These originated in most cases at a corner near the start of the radius on the free length of the specimen where the maximum bending stress, $\sigma_c + \sigma_m$, was produced.

As will be seen in the discussion of the S-N curves for the different metallurgical conditions, no definite fatigue limit was observed. This is generally the case for those nonferrous materials which do not exhibit strain aging.⁽³⁾ To provide a basis for comparison of the different metallurgical conditions studied, fatigue strength will be defined as the cyclic stress below which failure does not occur between 10^7 to 10^8 cycles.

RESULTS AND DISCUSSION

To evaluate the effect of metallurgical conditions on the fatigue behavior of the Pu-1.0 w/o Ga alloy, the following conditions were fatigue tested:

- a. Cored, as-cast, milled to size, average grain size 0.005 mm.
- b. Cored, 86% cold rolled,
 - (1) Milled specimens, contains 15% alpha phase,
 - (2) Punched specimens, contains 10% alpha phase,
- c. Cored, 86% cold rolled, specimens punched, longitudinal axis of symmetry, transverse to rolling direction, contains 12% alpha phase,
- d. Cored, 86% cold rolled, annealed 0.5 hour at 300 C, furnace cool, specimens punched, no alpha phase,
- e. Homogenized for 192 hours at 425 C, 94% cold rolled, no alpha phase,
- f. Homogenized for 192 hours at 425 C, 94% cold rolled, annealed for 0.5 hour at 300 C, no alpha phase.

The properties which may influence fatigue behavior for the above conditions are presented in Table I. Note that 0.1% yield strength ranges from 10,300 to 30,400 psi for metallurgical conditions ranging from as-cast to 94% cold rolled. Moduli of elasticity above 7.3×10^6 psi indicate that alpha phase with its 14×10^6 psi modulus is present. The density data confirm this observation. Poisson's ratio for the wrought alloy is roughly 25% lower than in the as-cast or annealed alloys, indicating a directionality effect. Total impurity contents and surface finish for the conditions tested are comparable.

TABLE I

PROPERTIES OF METALLURGICAL CONDITIONS TESTED

Material Condition	Approx. 0.1% Yield Strength (psi)	Approx. Ultimate Strength (psi)	Cyclic Fatigue Strength (psi)	Average Mean Stress (psi)	Modulus of Elasticity (10 ⁶ psi)	Poisson's Ratio (2)	Density (g/cc)	Diamond Pyramid Hardness (2Kg Load)	Gallium Content (w/o)	Total Impurity Content (ppm)	Surface Finish Range (RMS)	Average Vibration Frequency (Cycles/Sec.)
Cored, as-cast, milled to size, average grain size: 0.005 mm.	10,300	16,200	10,000	5,840	6.0	.245	15.81	46	0.92	215	30-70	205
Cored, 86% cold rolled Milled specimens	30,400	35,500	15,000	6,740	8.2	.160	16.31	60	0.88	355	20-25	218
Punched specimens	30,400	35,500	14,000	5,400	7.5	.166	16.12	72	0.95	340	7-20	234
Cored, 86% cold rolled, specimens punched, longitudinal axis of symmetry, transverse to rolling direction.	30,400	35,500	13,000	-	7.4	.199	16.20	72	0.91	1364	8-18	232
Cored, 86% cold rolled, annealed 0.5 hour at 300 C, furnace cool, specimens punched.	10,300	16,200	13,000	6,290	6.1	.251	15.77	43	1.00	340	8-28	212
Homogenized 192 hrs. at 425 C, 94% cold rolled.(3)	27,400	30,300	12,000	5,670	7.3	.183	15.74	56	0.92	352	10-25	228
Homogenized 192 hrs. at 425 C, 94% cold rolled, annealed 0.5 hr. at 300 C.(3)	10,300	16,200	10,000	6,000	5.5	.227	15.74	43	0.92	352	13-27	218

(1) Determined both with a linear differential transformer and 90° rosette strain gage.

(2) Determined with a 90° rosette strain gage.

(3) Punched specimens.

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The S-N curve for cored, as-cast and milled alloy is illustrated in Figure 1. Despite the scatter existing, the data suggest a fatigue strength of 10,000 psi. Internal casting defects observed on radiographs of some of the specimens are believed to be at least part of the reason for the scatter in the data. The 15.81 g/cc density on the specimens instead of the expected 15.76 g/cc value indicates that alpha phase formation occurred on the surface during milling. The formation of alpha phase results in strengthening and a volume contraction. The surface therefore may be in a complicated state, i.e., residual compressive stresses from milling and/or residual tensile stresses plus strengthening from alpha formation. To further complicate the picture, the 5,840 psi average mean stress during testing is 53% of the 10,300 psi 0.1% yield strength which by itself would tend to lower the fatigue strength.⁽⁴⁾ As will be shown later the 10,000 psi fatigue strength for homogenized, wrought, annealed and punched specimens indicates that the 10,000 psi fatigue strength for the cored, as-cast and milled alloy may be slightly high.

Two S-N curves for the cored as-rolled alloy are presented in Figure 1. One curve is for milled specimens and the other for specimens punched from as-rolled sheet which had been rolled to final thickness. The fatigue strengths for the milled and the punched specimens are approximately 15,000 and 14,000 psi, respectively. Since both fabrication methods produced comparable surface finishes, the higher fatigue strength for the milled specimens may be the result of their slightly larger amount of alpha phase, particularly on the milled surface. The mean stresses during testing were 6,740 and 5,400 psi respectively for the milled and the punched material during testing. Since these are only approximately 20% of the 30,400 psi, 0.1% yield strength, it is not expected that mean stress influenced the fatigue results.⁽⁴⁾

A comparison of S-N data from specimens punched both parallel and transverse to the rolling direction from the same sheet is illustrated in Figure 2. The fatigue strengths for both are essentially the same which is not unusual for a wrought cubic structure with a minimum of inclusion stringers. The high total impurity content of this sheet, Table I, was entirely due to the presence of 1,000 ppm nickel. Compared to the fatigue strength of similarly fabricated low nickel material, this may have caused a 1,000 psi decrease in the fatigue strength, although it is doubtful whether this magnitude of change is statistically significant.

Annealing the cored, as-rolled alloy in vacuo for 30 minutes at 300 C produces a dead soft delta phase condition with no alpha phase. The 0.1% yield strength decreases from 30,400 to 10,300 psi and the hardness decreased from 72 to 43 DPH. The fatigue strength, however, decreased only slightly from 15,000 psi before the anneal to 13,000 psi after the anneal, Figure 3. This indicates that fatigue strength is relatively insensitive to magnitude of yield strength in the alloy. The 6,380 psi mean stress in the annealed condition is 62% of the 10,300 psi, 0.1% yield stress and as in the as-cast alloy may have had an adverse effect on the indicated fatigue strength.

Figure 1

S-N DIAGRAM FOR Pu-1.0 w/o Ga ALLOY IN AS-CAST AND ROLLED CONDITIONS

Figure 2

S-N DIAGRAM FOR 86% COLD ROLLED, CORED Pu-1.0 w/o Ga ALLOY
TESTED PARALLEL AND TRANSVERSE TO ROLLING DIRECTION

Punched Specimens Tested at Room Temperature
Mean Stress 5,400 psi

Figure 3
S-N DIAGRAM FOR ROLLED PU-1.C w/o Ga ALLOY
IN CORED, HOMOGENIZED AND ANNEALED CONDITIONS
PUNCHED SPECIMENS TESTED AT ROOM TEMPERATURE

The homogenized, i.e., 192 hours at 425 C, and 94% rolled alloy had a 12,000 psi fatigue strength which was only slightly higher than the 10,000 psi fatigue strength for the same material after the 300 C, 30 minute anneal, Figure 3. Both fatigue strengths were somewhat lower than those obtained on similarly fabricated and annealed alloy in the cored condition. In the cored alloy, either the initial presence of alpha phase or its formation from the compressive stresses introduced during fatigue testing may have caused strengthening, i.e., increased fatigue resistance. In the homogenized and rolled condition the 5,670 psi mean stress was only 20% of the 27,400 psi, 0.1% yield stress therefore having little, if any, effect on fatigue strength. In the annealed condition the mean stress was 54% of the 10,300 psi, 0.1% yield stress which could have an adverse effect on fatigue strength as suggested for previous dead soft conditions.

From a visual standpoint, oxidation of the specimens during testing was not apparent. The normal oxide tarnish which forms soon after machining was not visibly affected.

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