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The Mechanical Properties of Alpha Plutonium in Compression.*

by

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ABSTRACT

The effect of temperature, testing speed and purity on the mechanical behavior of alpha plutonium in compression was investigated. The results of the tests were generally similar to those previously reported[2,3,4] except that specimen purity was observed to affect the results and a strain-aging reaction was also observed.

INTRODUCTION

The metal plutonium is an intriguing material. It has six allotropic modifications, two of which, alpha and beta, have a monoclinic structure[1] which is rarely found in pure metals. The first of these, alpha, is interesting because it is brittle when tested in tension but is relatively ductile when tested under compressive loading[2,3]. Because of this behavior it was decided that initial precise studies of the mechanical properties of alpha plutonium could best be carried out by using the compression test. In this way the effects of surface condition, internal defects and specimen alignment would be minimized.

The compression properties of alpha plutonium have been treated briefly by Miner, et al[2] and Bronisz and Gorum[4], and more extensively by Gardner and Mann[3]. The samples used by Gardner and Mann were machined from several different melts having total impurity contents ranging from 324 to 3468 ppm. Although their results did not show any significant effect of metal purity on the alpha phase properties, it was felt that it would be useful to conduct a complete series of experiments with specimens from the same melt and, presumably, having the same impurity content. A small amount of high purity plutonium was also available for testing and was compared with the less pure material.

In this report the effects of temperature, strain rate, and metal purity on the mechanical properties of alpha plutonium in compression are considered.

Material

The specimens used for the compression studies came from four melts of plutonium. The initial experiments were carried out with specimens machined from rods cast from a relatively pure button of plutonium obtained by the standard calcium reduction technique[5]. Later experiments were carried out with specimens that were machined either directly from a plutonium button obtained by electrorefining[6] or from rods obtained by remelting the electrorefined button either once or three times.

Samples of each of the four series of specimens were analyzed chemically. The results of these analyses are given in Table I. Examination of the chemical analysis results shows that the electrorefined metal was purer than the calcium reduced metal and that remelting the electrorefined plutonium using a standard technique, in MgO crucibles under dynamic vacua, decreases the silicon content but increases the iron content.

Metallographic examination of the material used for the compression tests confirmed the chemical analyses. Sections of the control samples, both in the as-polished and etched conditions, are shown in Figure 1. Photomicrograph 1a is of the calcium reduced material, while 1b and 1c, 1d and 1e, and 1f and 1g are photomicrographs of as-deposited, once remelted and thrice remelted electrorefined plutonium, respectively. The differences between the calcium reduced plutonium and the electrorefined plutonium are apparent in the larger grain size and the smaller amount of second phase in the latter. The three batches of electrorefined

Table I. Chemical Analyses of Plutonium used for Compression Testing.

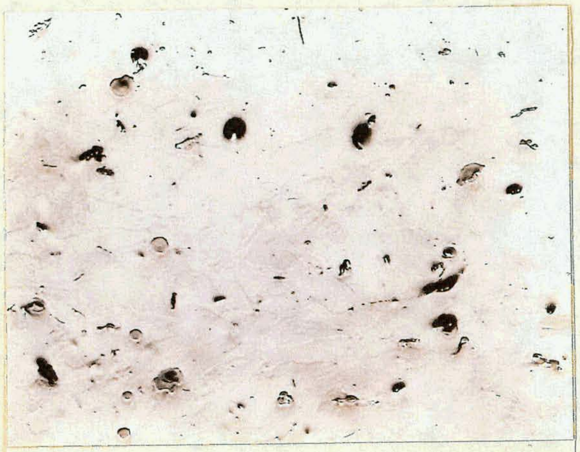
Element	Calcium Reduced Plutonium	Electrorefined Plutonium, as deposited	Electrorefined Plutonium, once remelted	Electrorefined Plutonium thrice remelted
Li	< 0.2 *	< 0.2	< 0.2	< 0.2
Be	< 0.2	< 0.1	< 0.1	< 0.1
Na	< 10	< 10	< 10	< 10
Mg	10	< 5	< 5	< 5
Ca	15	< 10	< 10	< 10
Al	15	15	15	15
La	< 10	< 10	< 10	< 10
Si	70	25	10	< 10
Pb	< 1	< 2	< 2	< 2
Cu	10	2	5	2
Ni	85	< 10	< 10	< 10
Cr	< 20	< 10	< 10	< 10
B	< 0.5	< 0.5	< 0.5	< 0.5
Mn	**	3	3	5
Sn	**	< 1	< 1	< 1
Bi	**	< 1	< 1	< 1
Fe	140	< 10	100	170
Co	**	< 10	< 10	< 10
Zn	**	10	< 10	10
F	< 2	< 2	< 2	< 2
C	135	60	52	25
Total Impurities†	480	115	185	227

* expressed as ppm

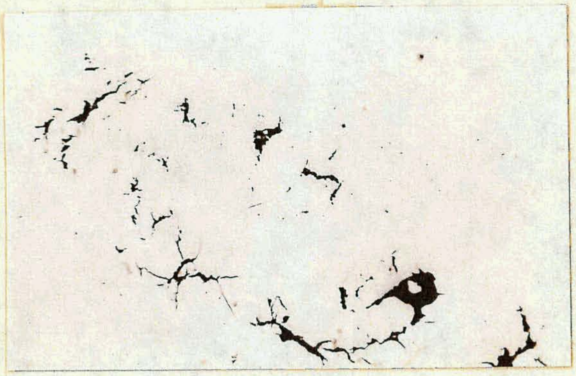
** not determined

† not including <'s

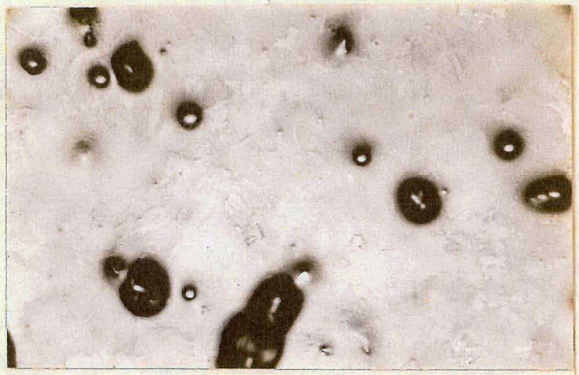
Figure 1. The microstructures of the plutonium specimens used in the compression tests. (a). calcium reduced plutonium, etched, 250X. (b). as-deposited electrorefined plutonium, as polished, 50X. (c). same, etched, 100X. (d). once remelted electrorefined plutonium, as polished, 50X. (e). same, etched, 100X. (f). thrice remelted electrorefined plutonium, as polished, 50 X. (g). same, etched, 100X.



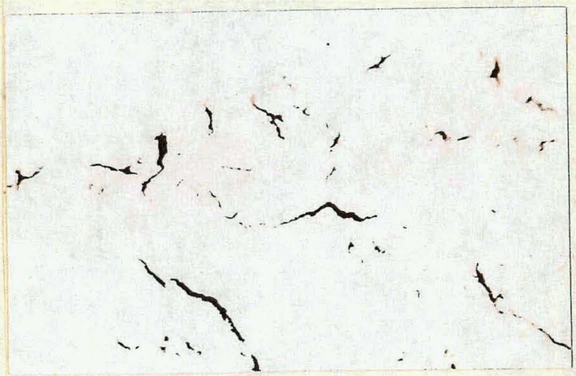
(a)



(b)

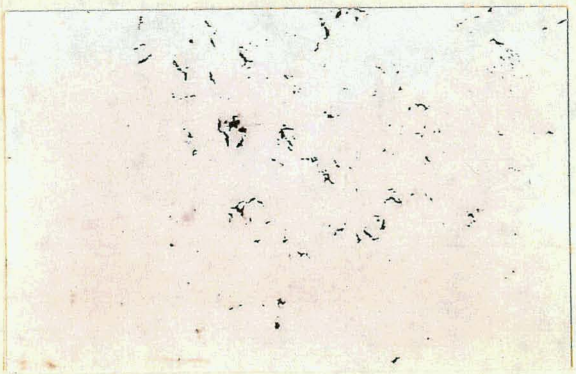


(c)



(d)

(e)



(f)

(g)

material differed among themselves in the amount of microcracking and the quantity of a second phase present. Examination of the analytical data and the photomicrographs leads to the conclusion that the second phase present in the electrorefined plutonium that was remelted three times is Pu_6Fe. It has been pointed out by Gardner[7] that the addition of several hundred ppm of iron will inhibit microcracking in alpha plutonium, and certainly the amount of cracking, as shown in Figure 1f, was decreased.

Experimental

The compression specimens were in the form of right cylinders 0.9 cm. long and 0.6 cm. in diameter. They were machined from the various as-cast materials described above and were given no subsequent heat treatment. The specimens were placed within a small sub-press that was held in an air-tight brass can, which acted both as a contamination barrier and as a constant temperature bath. The heat transfer medium used was degassed silicone vacuum pump oil.

The loading force was transmitted from the compression crosshead of an Instron testing machine through a bronze bellows in the top of the brass can to the upper platen of the sub-press. The loading speeds used were 0.005, 0.05, 0.5 and 5.0 cm/min. The tests were run at temperatures of 25 ± 1°, 50 ± 0.5°, 75 ± 0.5° and 100 ± 1°C. The heat was supplied by a heater external to the can.

For most of the tests, the loading was monotonic, but a few tests were run in which the load was cycled after every 1 or 1.5 per cent strain so that the ends of the specimen might conform to the sub-press platens and thus allow the region of uniform strain to be extended.

The results of the compression tests were obtained as load-crosshead-movement curves on the Instron recorder. By using suitable corrections for machine softness, the curves were converted to stress-strain curves. Because of the cracking present in the electrorefined plutonium and the uncertainty of the strain at which barreling began, only the yield strength, defined here as the proportional limit as measured on the load-extension curves, will be used for the comparisons drawn below.

Because only a small amount of the electrorefined plutonium was available, the range of testing speeds used at the various temperatures for this material was not covered as completely as it was for the calcium reduced plutonium.

Results

It was found that, for the given test conditions, the variation of yield strengths among the three series of specimens made from the electrorefined plutonium was generally less than 2 per cent and never more than 3.5 per cent, so the data for the three series were combined and treated as if they were from one series of specimens.

The load-crosshead-movement curves were similar for both types of plutonium. Monotonic loading at all speeds and at temperatures of 24°, 50°, and 75°C, produced smoothly varying curves, but monotonic loading at 100°C produced a curve with a broad initial yield point. The yield point maximum occurred at approximately 3 per cent and the minimum occurred at about 8 per cent nominal strain.

Results of the cyclic loading were also similar for the two materials. The cycling did result in an increase in the amount of uniform strain, but the stress-strain curve was appreciably modified by this technique. Cycling at room temperature caused an increase in the work hardening rate, as indicated in Figure 2. For nominal strains of 5, 10, and 14 per cent, respectively, the differences in observed flow stress are 10, 13 and 12 per cent for the calcium reduced plutonium and 3, 5, and 6 per cent for the electrorefined material.

On reloading after cycling at temperatures above 24°C, the increase in flow stress was even more marked than at room temperature. Not only was the flow stress increased but a broad yield point was also observed. This yield point was similar to the initial yield point observed at the test temperature of 100°C, in that the yield maximum was at 3 per cent strain and the minimum was at about 8 per cent strain with respect to the proportional limit observed on reloading.

The variation of yield strength with testing temperature is indicated in Figure 3. It may be seen that the yield strength of the higher purity, electrorefined plutonium is more dependent on testing temperature than is that of the lower purity, calcium reduced plutonium. The effect becomes more pronounced as the strain rate increases.

Figure 2. The effect of strain aging on the nominal stress-strain curves of alpha plutonium tested in compression at 25°C at a head speed of 0.02"/min.

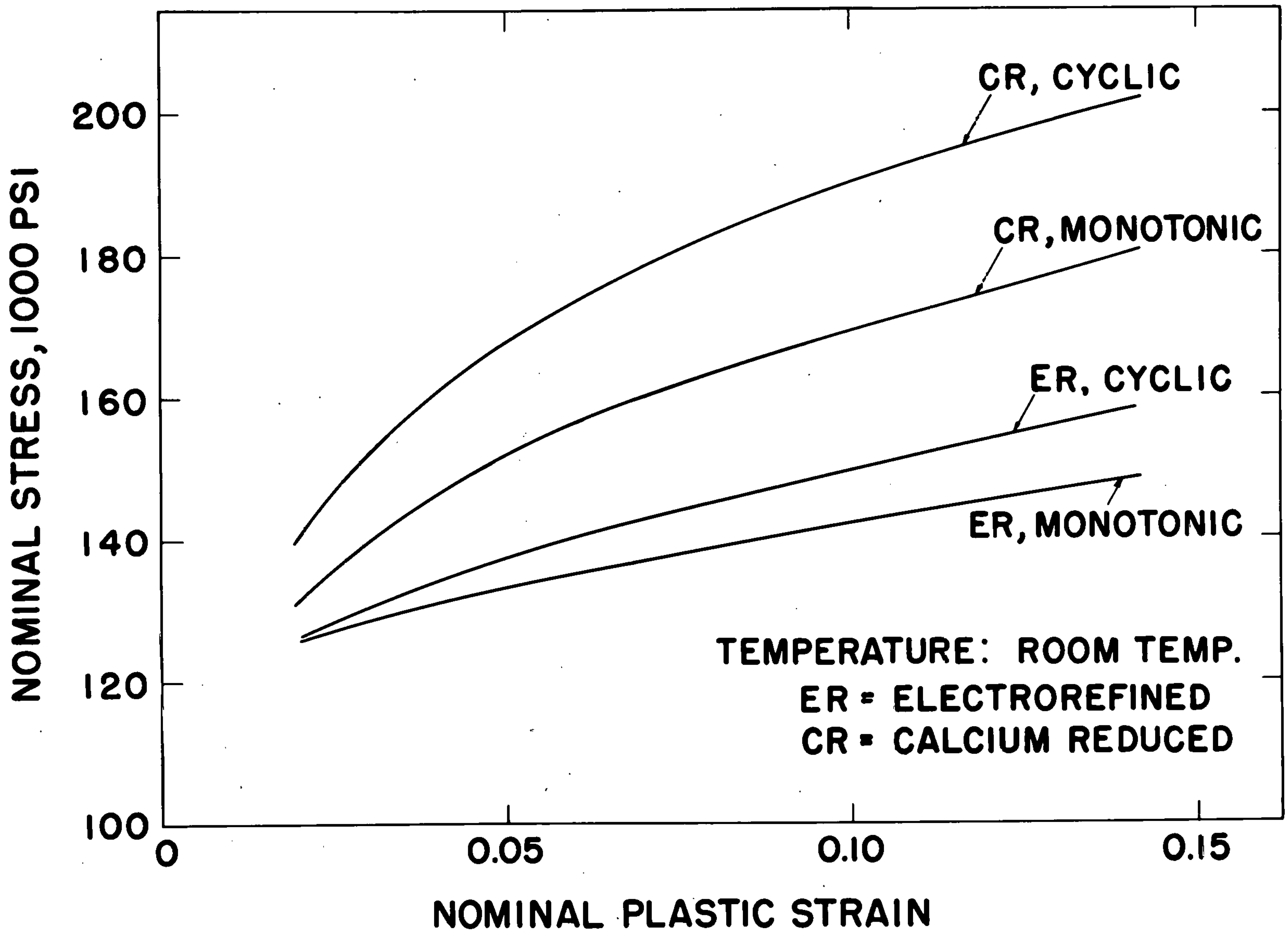
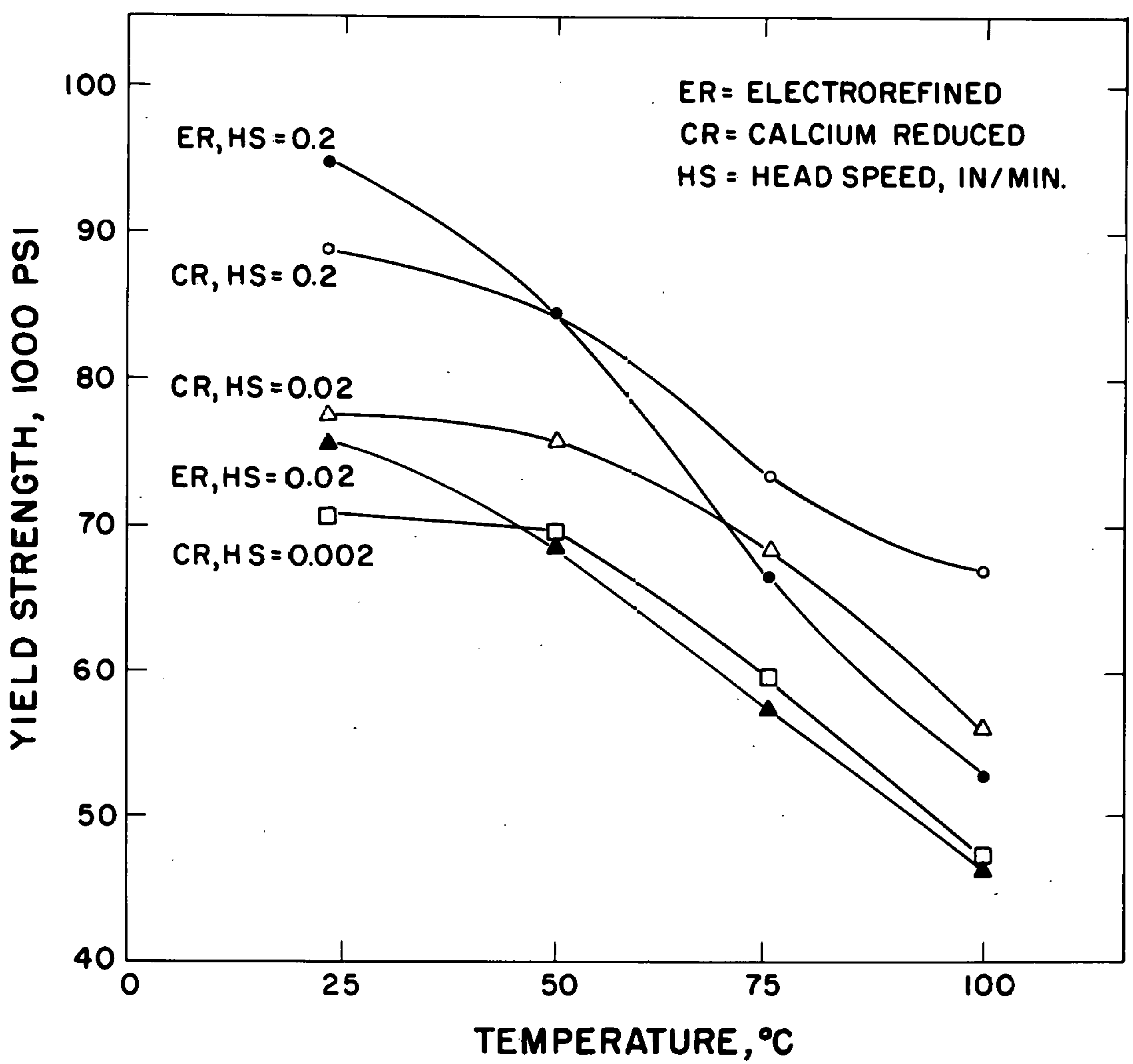

CR, CYCLIC
CR, MONOTONIC
ER, CYCLIC
ER, MONOTONIC
TEMPERATURE: ROOM TEMP.
ER = ELECTROREFINED
CR = CALCIUM REDUCED
NOMINAL STRESS, 1000 PSI
200
180
160
140
120
100
0
0.05
0.10
0.15
NOMINAL PLASTIC STRAIN

Figure 3. The effect of testing temperature on the compression yield strength of alpha plutonium at various testing speeds.



ER = ELECTROREFINED
CR = CALCIUM REDUCED
HS = HEAD SPEED, IN/MIN.
ER, HS = 0.2
CR, HS = 0.2
CR, HS = 0.02
ER, HS = 0.02
CR, HS = 0.002
YIELD STRENGTH, 1000 PSI
100
90
80
70
60
50
40
0
25
50
75
100
TEMPERATURE, °C

Figure 4 shows some of the data replotted to reveal the effect of testing speed on the yield strengths. Although the data for the electrorefined plutonium is not as extensive as that for the calcium reduced material, it is evident that the purer metal is the more sensitive to changes in testing speed. For both materials the sensitivity to testing speed decreases as the temperature increases (with the exception of the calcium reduced plutonium at 100°C).

When the two series of compression specimens were examined metallographically, the main difference observed was in the strain-induced microstructural features. Macroscopically, there was no difference in the appearance of the strained specimens. Both the electrorefined and the calcium reduced specimens had regions of relatively lightly deformed grains near their ends, because the ends of the specimens did not accommodate to the platens as the testing proceeded, and regions of great deformation in their centers where the flow was greatest Microscopically, it was found that the electrorefined plutonium specimens contained many more grains with twin-like markings than did the calcium reduced plutonium specimens. Examples of these twins are shown in Figure 5.

As was previously reported[4)], the frequency of twinning seemed to increase as the temperature of deformation of calcium reduced plutonium increased. Unfortunately, the small number of twins observed (1 per cent or less of the grains) made our attempts to count them relatively inaccurate, but the larger number of twins observed in the electrorefined plutonium indicated that better results could be expected with the purer

Figure 4. The effect of testing speed on the yield strength of alpha plutonium at various temperatures.

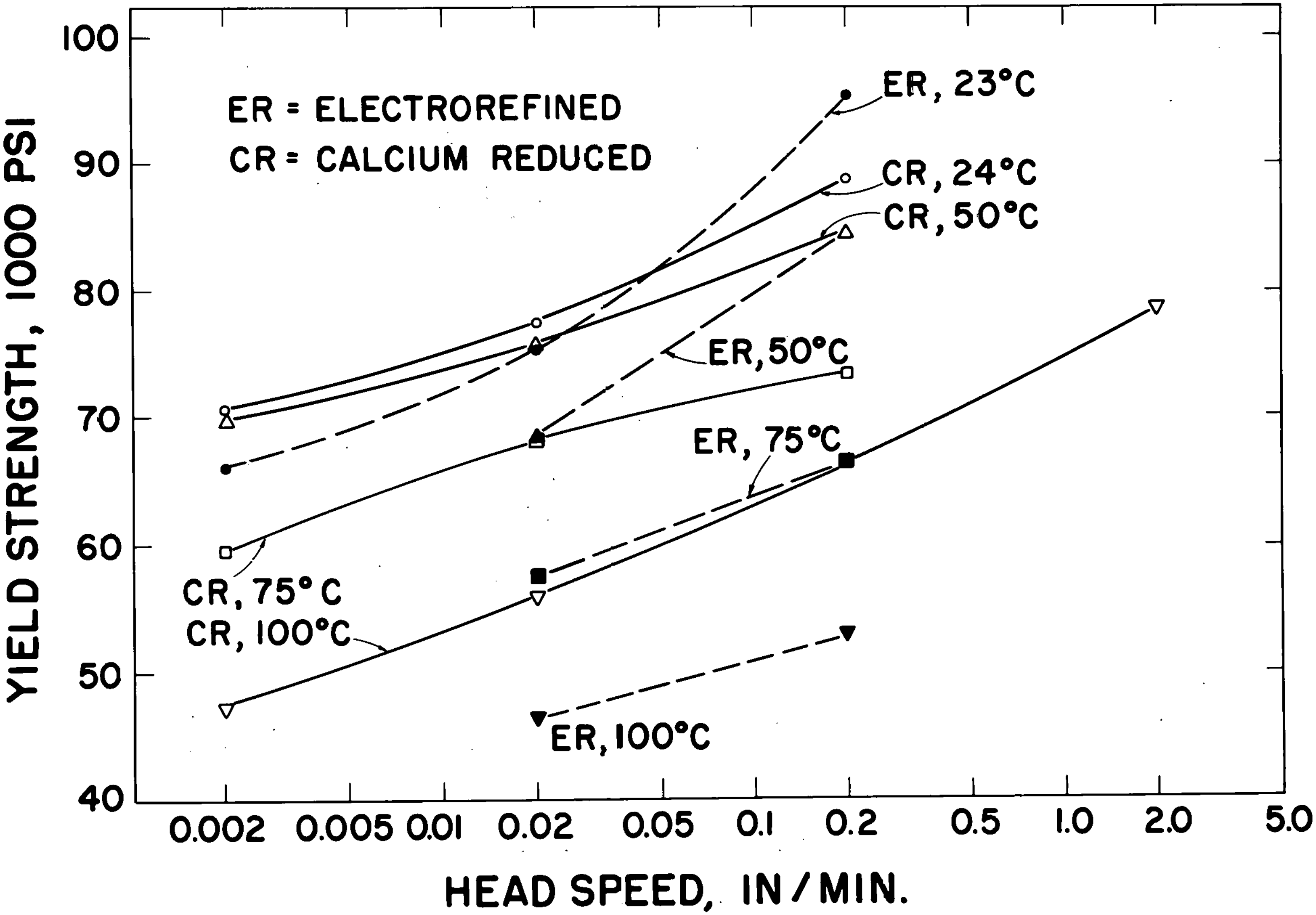
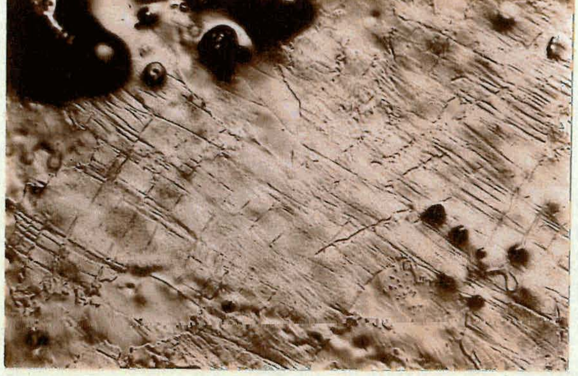
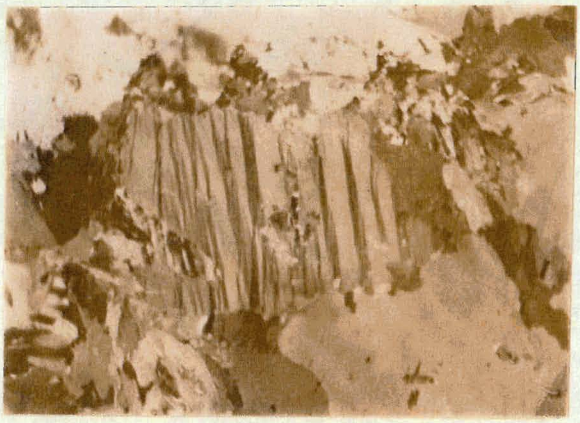

ER = ELECTROREFINED
CR = CALCIUM REDUCED
ER, 23°C
CR, 24°C
CR, 50°C
ER, 50°C
ER, 75°C
CR, 75° C
CR, 100°C
ER, 100°C
YIELD STRENGTH, 1000 PSI
100
90
80
70
60
50
40
0.002
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1.0
2.0
5.0
HEAD SPEED, IN / MIN.

Figure 5. Stress induced features in deformed alpha plutonium. These features are probably deformation twins but they have not yet been positively identified.

(a) 

(b) 

(c) 

material. Accordingly, the effect of testing temperature on frequency of twinning was determined for a series of electro-refined specimens that had been deformed at the various testing temperatures at a head speed of 0.02 in./min. By using a point counting technique the results shown in Table II were obtained. From the table, it may be seen that the testing temperature has little effect on the frequency of twinning in the electrorefined plutonium, over the temperature range investigated.

Discussion

The above observations concerning the mechanical behavior of alpha plutonium are generally those that were expected. The fact that the amount of strain-aging is greater for the material with the greater amount of impurity would be expected as would be the general trends in the behavior of the yield strength with temperature and strain rate.

The fact that an increase in temperature caused the strain-rate sensitivity of the yield stress to decrease, contrary to the usual observations for single-phase metals, was unexpected, but it may be related to strain-aging.

The increase in twin frequency with purity was expected, if the evidence for the increase in twinning ease with purity observed for bcc metals can be extrapolated to include the monoclinic structure of plutonium. It is not likely that the ease of twinning in alpha plutonium is unaffected by temperature; the temperature range of our studies may not have been wide enough to demonstrate such an effect.

The yield strength values determined during this series of

Table II. Effect of Temperature on the Fraction of Grains Twinned During Deformation (Head Speed: 0.2"in./min.)

Test Temperature, °C.	Fraction Twinned
23	0.21
50	0.18
75	0.18
100	0.19
100	0.18

experiments were generally lower and exhibited a somewhat different temperature and strain rate dependence than did those reported by Gardner and Mann[3]. At the present stage of knowledge concerning the mechanical properties of alpha plutonium, it is not possible to determine the exact causes of these discrepancies, but they are probably due to differences in the purities of the plutonium specimens, in the testing machines or in the testing techniques used, or to some combination of these factors.

Conclusions

1. Alpha plutonium exhibits a strain-aging reaction that is less prominent for metal of high purity than for metal of slightly lower purity.

2. The yield strength of alpha plutonium decreases as the testing temperature increases. This effect is more pronounced for the purer material.

3. The effect of testing speed on the yield strength of alpha plutonium is normal; i.e., as the speed increases the yield strength increases.

4. An increase in testing temperature causes a decrease in the testing-speed sensitivity of the yield strength, contrary to the usual observation for other materials.

5. Plutonium of high purity twins more easily than does plutonium of standard purity.

6. At a testing speed of 0.2 in./min., there was no apparent change in the frequency of deformation twins in the temperature range between 24° and 100°C.

7. The reasons for the differences between some of our present results and those obtained previously are probably due to differences in the purities of the various plutonium specimens, or in the testing machines and techniques used in the two series of experiments.

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