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DEFORMATION OF CRYSTALS OF ALPHA PLUTONIUM IN COMPRESSION

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DEFORMATION OF CRYSTALS OF ALPHA PLUTONIUM IN COMPRESSION*

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The crystal structure of alpha plutonium is complex and of low symmetry (monoclinic, space group $P2_1/m$). Several slip planes have been suggested, namely, (020) and (001). Investigators at Los Alamos have reported that slip planes near (114), (213), and (323) are operative at room temperature in small-grained specimens. In the present study, large crystals of alpha plutonium (to $2 \times 2 \times 5$ mm) were prepared by high-pressure techniques. The results of a study to identify the deformation mechanisms and the stress-strain characteristics of alpha plutonium at room temperature are reported. All tests were compressive. The slip planes were identified by two-surface analysis.

Slip was the dominant deformation mechanism; however, some evidence suggests that twinning deformations were present. Results have shown that several slip planes are operative, apparently depending on the crystallographic direction of strain. Although most samples revealed only one slip plane, three planes were noted in one compression sample. The following slip planes were identified: $(\bar{1}02)$, (112), (111), (101), $(\bar{4}1\bar{1})$, (118), $(\bar{2}1\bar{3})$, (323), (415), (100), and (010). Plastic deformation was usually less than 1%; but in one case, deformation was over 13%. Most samples taken to failure exhibited brittle fracture.

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

Introduction

The crystallographic aspects of metal deformation are now reasonably understood, although most of the effort thus far has been directed towards metals with high symmetry, such as cubic and hexagonal. In face-centered cubic metals, the slip plane is usually the most densely packed plane in the lattice, namely (111). This is also true of the hexagonal close-packed metals, where the basal plane (0001) is generally the dominant slip plane. In body-centered cubic lattices, slip may proceed on several planes, all having a high atomic density; however, the slip direction is almost always the closest-packed direction in the slip plane.

The crystal structure of alpha plutonium is complex, with low symmetry. The structure is monoclinic, space group $(P2_1/m)$, with 16 atoms in the unit cell⁽¹⁾. Conjectures on possible slip elements are very speculative because of the complex structure. Attempts to characterize the deformation systems have been frustrated, no doubt, by the unavailability of large crystals for experimental study. Early attempts to establish deformation planes in alpha plutonium have been directed towards (020). This plane has relatively high atomic density and is the only ideally flat plane in the crystal structure.

Spriet^(2,3) has reported that (020) is the dominant slip plane, based on studies of polycrystalline samples at room temperature. Bronisz and Tate⁽⁴⁾, using relatively small crystals, have reported that slip planes near (114), (213), and $(\bar{3}2\bar{3})$ probably are operative at room temperature. They state that no evidence has been found that (020) is a very important slip plane.

The purpose of this investigation has been to study the deformation elements of alpha plutonium at room temperature, and to identify these quantitatively by two-surface analysis.

Experimental Techniques

Large crystals of alpha plutonium were grown by the phase-transformation technique at pressures of 55 kbar⁽⁵⁾. Prismatic specimens were prepared by removing large cubes by grinding. Surfaces were prepared metallographically by successive grinding, lapping, and chemical polishing techniques previously reported⁽⁶⁾. A typical specimen is shown in Figure 1.

All of the plutonium had been purified by fused-salt electrorefining⁽⁷⁾. The total impurity content, exclusive of americium, was about 300 ppm by weight. The americium content, which was due to decay of ^{241}Pu , was about 200 ppm at the time of experiments.

Crystallographic orientations were determined by back-reflection Laue techniques⁽⁶⁾. At least two surfaces of the deformation specimen were indexed; in many cases, three or four surfaces were oriented (see Figure 1).

Deformation specimens were strained in compression on an Instron testing machine. Crosshead displacement was 0.002 in. per min (nominal strain rate $\sim 2\%$

per min). The deformation markings then were photographed. Two-surface analysis was used to determine the crystallographic planes of the deformation markings, with an accuracy of ± 3 deg.

Results and Discussion

The load-displacement characteristics of the specimens are shown in Figure 2. Six of the samples failed shortly after deviating from a linear load-displacement relationship. Specimen J was subjected to a total strain of over 16% and was noticeably barrel-shaped after straining. Specimen F partially failed at about 320 lb.

From the data shown in Figure 2, nominal values of yield stress and elastic modulus were calculated (see Table I). Yield stress was taken as the marked deviation from linearity of the load-displacement curve. Nominal strains ($\Delta l/l_0$) and initial areas (A_0) were used in all calculations. Values of yield stresses ranged from 34,200 psi to 101,000 psi, whereas values of the elastic modulus ranged from 0.51×10^6 psi to 1.30×10^6 psi.

Microphotographs of two surfaces of Specimen E are shown in Figure 3. The dominant slip plane was (112); however, a limited amount of slip was noted on the (010) plane.

Slip planes determined by the two-surface analysis in this study, plus those reported by Bronisz and Tate⁽⁴⁾, are shown in Figure 4. The planes given are within ± 2 deg of the two-surface solution. The results are somewhat puzzling for a crystal-line material. Each specimen tested revealed a different slip plane. The only plane duplicated was (112). In the two specimens where (010) was a result of two-surface analysis, only a limited amount of plastic deformation was observed; only a few slip

Table I. Summary of Data and Results

Specimen	Compression Direction	Slip Plane	Nominal Yield Stress (P/A_0 - psi)	Nominal Elastic Modulus (psi $\times 10^6$)	Area A_0 (in. ²)	Length l_0 (in.)
A	[230]	(102)	93,000	-	0.0050	0.111
B	[213]	(118)	83,700	1.05	.0105	.200
C	[441]	(101)	101,000	1.30	.0021	.107
D	[721]	(111) & (411)	40,600	0.78	.0016	.115
E	[1132]	(112) & (010)	65,300	0.77	.0052	.071
F	[010]	(112)	84,300	1.18	.0038	.130
G	[010]	(323)	50,000	1.05	.0034	.135
H	[3111]	(213)	48,200	0.68	.0028	.071
I	[931]	(100)	56,500	0.62	.0046	.098
J	[681]	(415)	34,200	0.61	.0038	.112
K	[581]	(010)	36,700	0.51	0.0049	0.085

lines were observed and used in the analysis. The slip planes observed in this study were generally within 10 deg of the maximum shear plane (45 deg to compression axis) and covered a broad orientation spectrum in the (010) standard projection of plane poles (Figure 4).

It was a general practice to re-polish specimen surfaces after straining and photographing. Twinning deformations were observed in only one case; the extent of twinning was very limited and could not be projected by two-surface analysis. Therefore, in this study (at room temperature), twinning could not be said to be a major deformation element.

Other studies of deformation mechanisms in monoclinic structures usually have been limited to geologic materials. In these studies, slip has been observed generally on only one plane(8). In the majority of cases, this plane has been (100), (010), or (001). The results of this study show many slip planes to be operative, apparently depending on the crystallographic strain direction. One factor which may explain these perplexing results is the temperature at which the tests have been conducted: room temperature. Since the melting temperature of plutonium is 640°C, T/T_m is approximately 1/3, a relatively high value. Generally in metal systems, the number of slip planes increases as the temperature increases. Extending the experimental parameters to include lower and higher temperatures, and enlarging the room temperature studies to include a wider range of crystallographic strain directions, would be helpful in explaining the deformation elements operative in alpha plutonium.

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Liptai - Fig. 1

Liptai - Fig. 2

Liptoi - Fig. 3

Liptai - Fig. 4