BNWL-SA-5324
Conf-750915--17

MECHANICAL PROPERTIES OF α-NEPTUNIUM: HARDNESS AND ELASTIC MODULI*

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A study of hardness and elastic moduli of α-neptunium was conducted. The hardnesses at 203, 240 and 298°K were 418, 395, and 346 Dph, respectively. The high hardnesses were attributed to the low symmetry of α-neptunium and the large number of twins in the microstructure. Unusual deformation twinning and slip were observed near the hardness indentations. A second twinning mode, in addition to the reported {110} mode, was suggested by the observations. This twinning was characterized by very narrow, straight twins in contrast to the wide, highly curved twins observed previously in polycrystalline α-neptunium. An ultrasonic method was used to measure sound velocities at 77 to 373°K. Elastic moduli and poisson's ratio were calculated from the sound velocities. The room temperature values for the moduli were: $B = 11.7 \times 10^{11}$ dyne/cm^2; $G = 8.28 \times 10^{11}$ dyne/cm^2; and $\sigma = 0.22$. The values were very nearly the same as the reported moduli of α-uranium.

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MECHANICAL PROPERTIES OF α-NEPTUNIUM: HARDNESS AND ELASTIC MODULI*

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The hardness of orthorhombic α-neptunium was 418, 395 and 346 Dph at 203, 240 and 298°K, respectively. The high values of hardness were attributed to the high stresses required for deformation twinning in highly twinned grains. Deformation twinning always occurred around the hardness indentations; slip was also observed. A second twinning mode in addition to the reported {110} mode was suggested by the observations. Shear and bulk moduli were measured from 77 to 373°K; the values at 298°K were 8.28 x 10^{11} and 11.7 x 10^{11} dyne/cm^2, respectively.

INTRODUCTION

Neptunium is intriguing because of its position in the periodic table between two metals with very different properties. Uranium has three allotropes and a relatively high melting temperature while plutonium has six allotropes and a relatively low melting temperature. The melting temperature of neptunium is close to that of plutonium but in other respects it is more like uranium. Neptunium has three allotropes and the low temperature form is orthorhombic as is α-uranium. Twins are profuse in α-neptunium, again like α-uranium. Twins are rarely observed in monoclinic α-plutonium. Little is known about the deformation of α-neptunium, however, and no measurements of elastic moduli were reported. This paper presents some preliminary measurements of moduli and observations on deformation modes around hardness indentations.

Electrorefined neptunium metal, obtained from Los Alamos Scientific Laboratory, was of very high purity as indicated by chemical analysis, density and metallography. The principal impurities in ppm by weight were: 10 Na, 4 Mg, 2 K, 2 Ca, 20 Fe, 2 Pb, 33 Th, 640 Pu-239 + Pu-240, 1.7 Pu-238 and less than 93 for other metallic impurities. The density at 25°C was 20.44 g/cm^3, very close to the theoretical X-ray density of 20.45 g/cm^3. Very few second phase inclusions were apparent in the microstructure. The grains were 0.5 to 1 mm in diameter and many twins were present as noted earlier in α-neptunium [1].

HARDNESS MEASUREMENTS

A tukon hardness tester with a symmetrical pyramidal diamond with 2 Kg load was used. The specimen was metallographically polished and etched for the tests. The selection of 2 Kg load was based on initial measurements which indicated a lower standard deviation with 2 Kg compared to 0.5 and 1 Kg. At the two lower loads there was a wide variation in the hardness values when indentations were made at random on the specimen surface, fig. 1. Even with 2 Kg load (indentation size approximately 100 μm) the hardness varied considerably, fig. 2. Apparently there are some microstructural features, possibly grain orientation or twin boundaries, which cause certain regions to have high hardness (this variation in hardness was not observed on a 350 Dph steel hardness standard checked periodically during the course of testing). To obtain reproducible averages, 30 to 50 indentations were made at each temperature.

*This paper is based on work performed under United States Energy Research and Development Administration Contract AT(45-1)-1830.

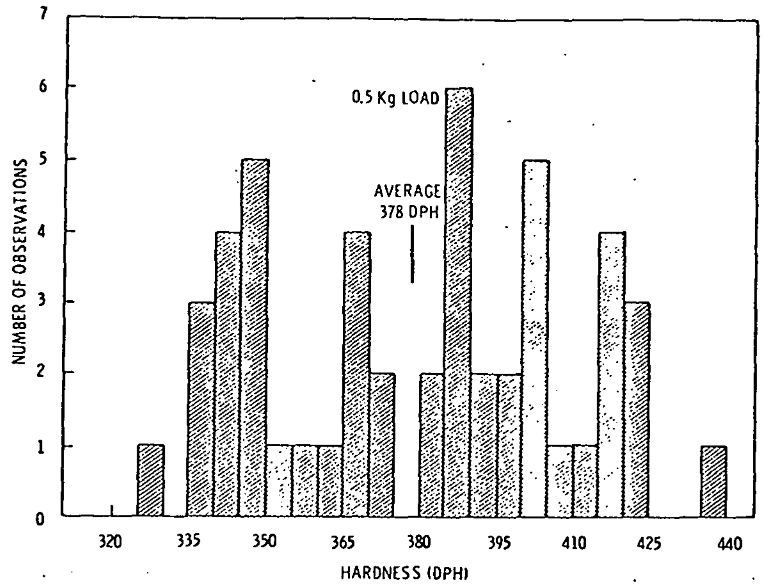

Figure 1. Histogram of Hardness Values at 240°K with 0.5 Kg Load

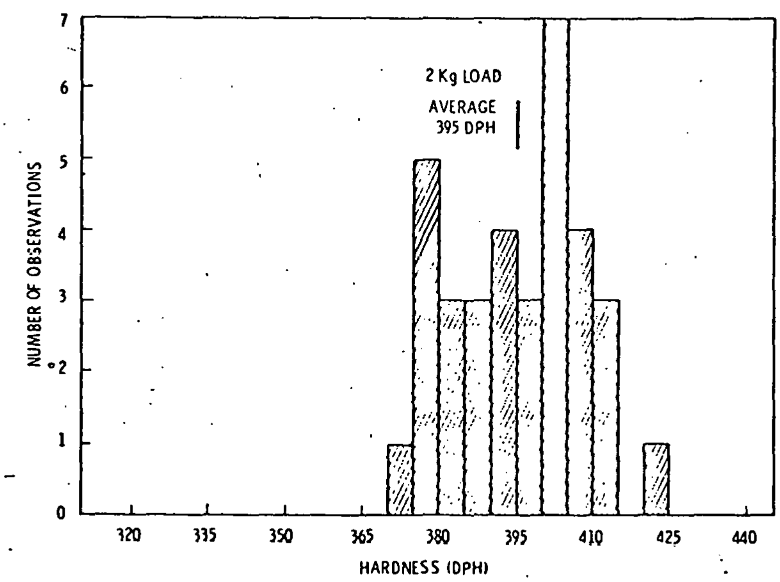

Figure 2. Histogram of Hardness Values at 240°K with 2 Kg Load

For the low temperature tests, the mounted specimen was immersed in FC-43 (3M Company, inert fluorochemical) which was cooled by adding dry ice. The indenter was precooled in the same bath. A series of indentations was made and the specimen was warmed to 25°C for measuring the indentation size. Thermal expansion corrections (≤1%) were ignored.

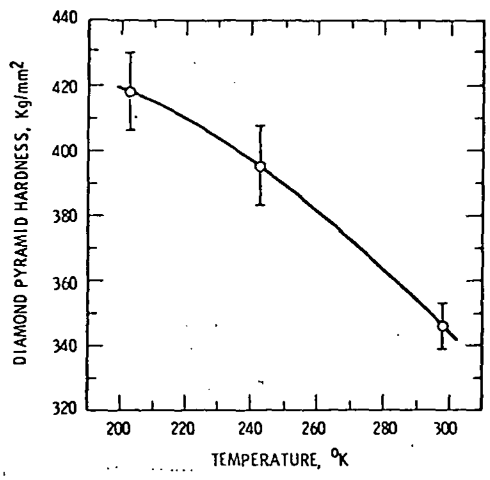

Figure 3. Hardness of α-Neptunium versus Temperature

The average hardnesses were 346, 395 and 418 Dph at 298, 240 and 203°K, respectively, fig. 3. The hardness indentations were examined by light microscopy and scanning electron microscopy. The most striking feature was the extensive deformation twinning at all three test temperatures, figs. 4-7. Twin-twin intersections were found around several indentations, fig. 4, region A. The traces near region B were slip on two planes; these lines disappeared on polishing and re-etching, fig. 5, whereas the twins at A were still visible. Very narrow twins were also observed crossing the faint, curved twins, fig. 6. An obvious change in the direction occurred when these twins crossed the faintly visible twins. Another characteristic pattern of deformation consisted of very curved twins emanating from the indentation along with distinct slip traces, 3 directions in this case, fig. 7. The slip lines change direction only very slightly on crossing these twins. Test temperature did not affect the deformation noticeably for the three temperatures tested so far. This was confirmed by placing an indent in one grain at both 298 and 203°K; the strain mode was almost identical.

ELASTIC MODULI MEASUREMENTS

Bulk and shear moduli were determined from ultrasonic measurements over the range 77 to 373°K. Longitudinal and shear wave velocities at 5 Mhz were measured with the pulse-overlap technique [2], fig. 8. The sample (1.16 cm diameter by 0.68 cm) was held by a spring against the end of a low carbon steel buffer rod. The upper end of the buffer rod where the transducers were placed was held at 300 to 320°K. The lower end of the rod and the specimen were immersed in a bath at the test temperatures.

Shear and bulk moduli, G and B, were calculated from the sound velocity data, table 1, according to

$$G = \rho V_s^2$$

$$B = \rho(V_l^2 - 4V_s^2/3)$$

where ρ is the density and V_l and V_s are the longitudinal and shear velocities, respectively.

Density and specimen length were not corrected for thermal expansion since low temperature expansion data are not available. The correction would be less than 1%, in any case. The moduli are plotted versus temperature, fig. 9.

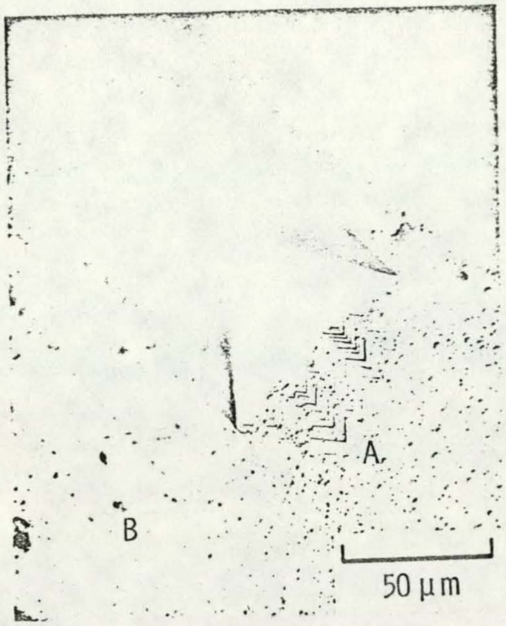

Figure 4. Hardness Indentations at 298°K Region A Zigzag Traces are Twin-Twin Intersections. Region B Contains Slip Traces.

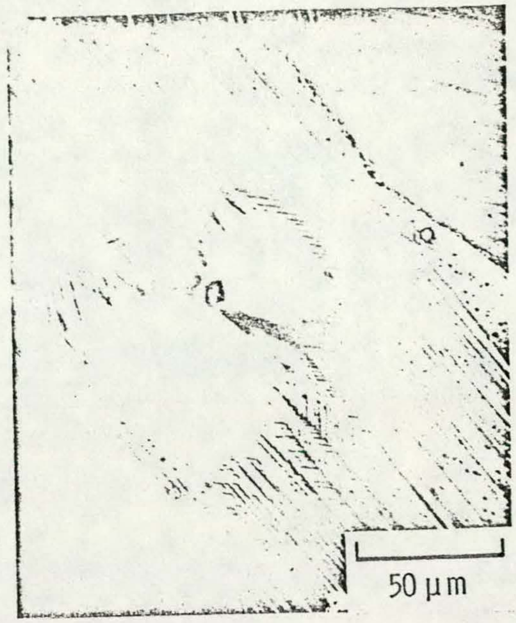

Figure 5. Same Indentation as fig. 4 After Repolishing and Etching. Slip Traces are Gone and Twins Remain. The very long twins are present in the as-cast microstructure.

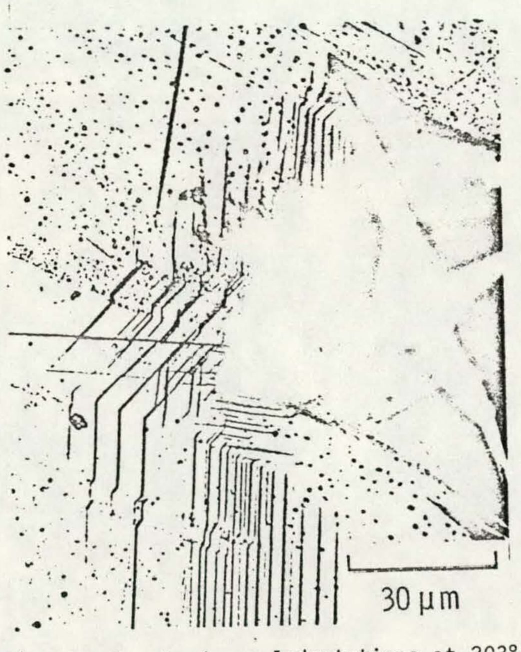

Figure 6. Hardness Indentations at 203°K Curved Twins are Crossed by Narrow Twins

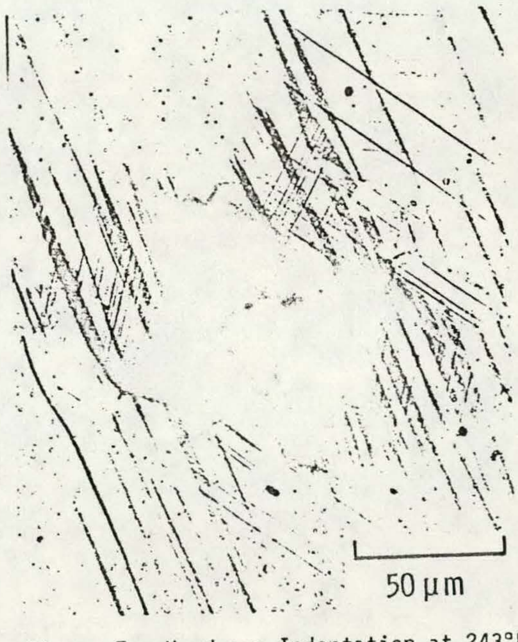

Figure 7. Hardness Indentation at 243°K Showing Curved Twins and Slip

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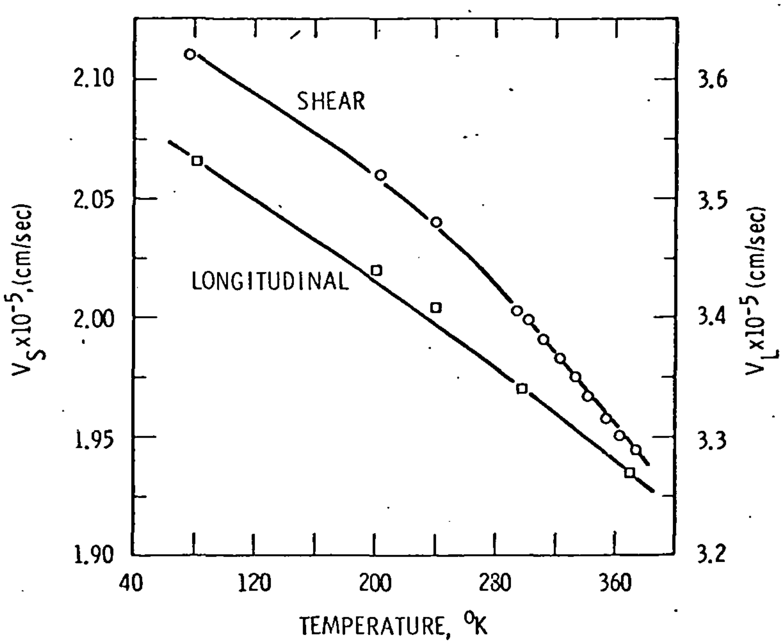

Figure 8. Sound Velocities in α-Neptunium versus Temperature

Table 1
Sound Velocity and Elastic Moduli of α-Neptunium

Temp °K	$V_l \times 10^{-5}$ cm/sec	$V_s \times 10^{-5}$ cm/sec	σ	$E \times 10^{-11}$ dyne/cm^2	$B \times 10^{-11}$ dyne/cm^2	$G \times 10^{-11}$ dyne/cm^2
373	3.26	1.94	0.224	18.9	11.4	7.73
298	3.34	2.00	0.220	20.0	11.9	8.20
240	3.41	2.04	0.222	20.7	12.4	8.48
203	3.44	2.06	0.220	21.1	12.6	8.66
77	3.53	2.11	0.220	22.3	13.2	9.13

DISCUSSION OF RESULTS

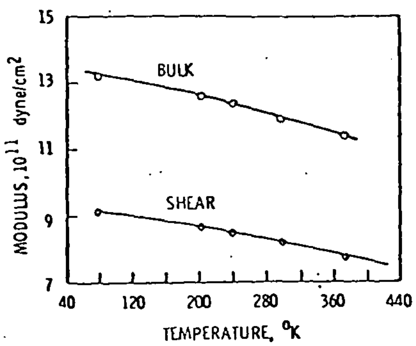

Figure 9. Bulk and Shear Moduli versus Temperature

The high hardness of α-neptunium (346 Dph at room temperature) can be reasonably attributed to the complex crystal structure and lack of many slip systems. The profuse deformation twinning can be taken as evidence that few slip systems exist and they require a high resolved shear stress for yielding. When compared to orthorhombic α-uranium (200-250 Dph at room temperature), the hardness is even more striking, especially in view of the homologous temperature, probably greater than 0.5 for α-neptunium and about 0.25 for α-uranium. This high hardness may be the result of high stresses required for deformation twinning in the already highly twinned grains. Grain boundaries did not seem to have much effect on hardness or on the shape of an indentation when it was near a grain boundary. Rechtein et al., [1] concluded that the $\{110\}\{1\bar{1}0\}\langle 1\bar{1}0\rangle\langle 110\rangle$ twinning mode with a very low shear of 0.063 was operative along with the conjugate mode in α-neptunium and that the second most likely mode (unobserved to date) was $\{011\}\{01\bar{1}\}\langle 01\bar{1}\rangle\langle 011\rangle$ with a very high shear of 0.63. The low shear of the $\{110\}$ mode was suggested as the reason for the highly curved shape of twins seen in polycrystalline samples.

No conclusions can be made yet, but the twins around some of the indentations appear to be of a different mode than the usual curved twins observed, e.g., fig. 4, region A. These zig-zagging twins cross alternately the curved twins thought to be the $\{110\}$ mode. Thus there is some evidence of an additional twinning mode, possibly the suggested $\{011\}$ mode. The curved twins of fig. 7 are probably the low shear $\{110\}$ mode. The small orientation difference across a twin boundary of this mode would explain the almost imperceptible change in direction of slip traces in crossing the twins. Further experiments on orientation determinations will be necessary to confirm these suggestions.

The moduli of α-neptunium at 298°K were very nearly the same as α-uranium at the same temperature. The similar crystal structures may account for this. However, the moduli of γ-plutonium, also orthorhombic, and α-plutonium are much lower than α-neptunium. The Debye temperature was calculated from the 77°K sound velocity data and was 260°K, close to that of α-uranium 248°K [3]. Thus the elastic properties of polycrystalline α-neptunium were similar to α-uranium and very different from plutonium.

Acknowledgements

The authors are grateful to J. Hammer for designing and building the sound velocity cell and for making the hardness measurements. This work was supported by the Division of Physical Research, U. S. Energy Research and Development Administration.

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