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A COMPARISON OF THE ELASTIC CONSTANTS FOR ROLLED URANIUM BARS AT 25°C AND 300°C

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Mechanics Division

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Metallurgy and
Ceramics

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Abstract

A measurement of the Young's Modulus, Shear Modulus, and Poisson's Ratio is described using ultrasonic pulses of approximately 3 mc/sec. The specimens used were in the form of "uncanned" bars about 8 inches long and 1 inch in diameter, some of which had detailed fabrication histories available. An electric furnace with helium atmosphere is described which permitted ultrasonic tests to be made at 300°C. In general, the elastic constants were reduced by about 15% at 300°C, compared to room temperature values.

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Introduction

The elastic properties of uranium are known to be highly dependent upon previous mechanical history¹. However, the constants determined at low stress levels, which is the case for ultrasonic measurements, seem to be reproducible to within a few percent for specimens of similar history. The elastic constants have been determined under this condition of low stress at temperatures approximating those existing inside some nuclear reactors now in operation. The specimens used were non-irradiated uranium. It is not known to what extent the elastic constants would be modified by irradiation.

Experimental Procedure

The ultrasonic velocity measurements were made at frequencies in the 1 to 3 megacycle range. Two quartz crystals of appropriate shape and thickness were placed on opposite ends of the specimen under study, one crystal being excited as a transmitter of ultrasonic energy while the other, with the necessary amplification, is used as a detector for the impulses which have travelled through the specimen. The transmitting crystal was excited by a square wave generator producing pulses of 50 volts amplitude and having a duration of about one half the resonant period of the quartz plate when attached to the specimen. By adjusting the pulse length for maximum signal amplitude, adequate energy levels could be obtained for at least a single trip along the axis of the 8 inch long rods. The limitation on pulse length to approximately half the transducer resonant period restricts the application of this electronic technique to frequencies less than about five megacycles.

This experimental technique and the method employed here for computing Young's Modulus and Poisson's Ratio are essentially the same as described by Hughes, Pondrom and Mims² (referred to subsequently as HPM). The computation requires the arrival time of the directly transmitted elastic pulse and also the arrival times of so called "delayed wave trains" or subsidiary pulses. These latter signals, as explained in HPM are the result of a continuous conversion into shear waves, at the rod's free surface, of the longitudinal waves composing the primary pulse. These shear waves, after obliquely

¹ E.R.W. Jones and W. Munro, Journal Mechanics and Physics of Solids 1:182(1953)

² D.S. Hughes, W.L. Pondrom, R.L. Mims, Phys. Rev. 75:1552(1949)

traversing the width of the rod, again revert to longitudinal waves at the rod's free surface and form a new wave front which is detected upon its arrival at the end of the bar. The subsidiaries are delayed in arrival time since the oblique path taken across the bar as shear waves was at a lower velocity, and the total distance travelled is greater than that for the first arrival. Figures 1 and 2 show typical displays of this phenomenon in alpha and beta treated bars of uranium respectively. At the extreme left of each trace is a marker pulse indicating the starting time for the pulse sent into the bar. The travel time for the directly transmitted longitudinal pulse in the 8 inch long bars at room temperature is about 61 microseconds. This signal is followed by subsidiaries at intervals of about 9.3 microseconds. The time interval between the subsidiaries is a function of the bar diameter. A rearrangement of the equations given in HPM leads to the following expression for Poisson's Ratio:

$$\nu = \frac{1}{2} - \frac{1}{2} \frac{D^2}{L^2} \left(\frac{\Delta t_L}{\Delta t_S} \right)^2 \quad (1)$$

where D is the diameter and L the length of the bars, while Δt_L is the transit time for the longitudinal wave along the bar axis and Δt_S is the time between successive subsidiary arrivals.

Having obtained a value for Poisson's Ratio, ν , and the longitudinal velocity, V_L , along the bar axis, it is possible to compute the shear velocity, V_S , from the relation:

$$V_S = V_L \left(\frac{1 - 2\nu}{2(1 - \nu)} \right)^{1/2} \quad (2)$$

Likewise Young's Modulus, E, can be obtained from the relationship:

$$E = \frac{V_L^2 \rho (1 + \nu)(1 - 2\nu)}{(1 - \nu)} \quad (3)$$

where ρ is the density.

In view of the known inelastic behavior of uranium, it was considered desirable to compare the elastic constants obtained from ultrasonic data with those determined in a conventional testing machine. Bonded wire strain gages were cemented to the central portion of the bar so as to measure both longitudinal and circumferential strain simultaneously. The bar was subjected to a compressive stress reaching a maximum value of about 1.7×10^8 dynes/cm².

An effort was made to extend the information on elastic constants to the temperature range prevailing in some nuclear reactors using the slug type fuel. In order to heat the specimens, a brass tube was constructed with quartz crystal holders in each end. Gas fittings were provided so that an atmosphere of helium could be maintained around the specimen at all times to prevent excessive oxidation. Figures 3 and 4 illustrate this arrangement diagrammatically. The interface between the quartz transducers and the end of the bar was moistened with a silicone type oil which was stable for a sufficiently long time at 300°C to permit ultrasonic measurements to be made. The piezo-electric constant for quartz becomes weaker as the temperature is increased. The ultrasonic signal consequently deteriorates rapidly, but is still usable at 300°C.

The velocity calculations require a correction for the new length of the bar due to expansion. Hence, before making the ultrasonic measurement, a preliminary heating was performed in the same apparatus with an extensometer attached to each end of the specimen. This gave only the coefficient of expansion along the polycrystalline bar axis. For the density adjustment at the elevated temperatures an average value of the expansion coefficients for the single crystal was used³.

The bars used for this investigation are described in Table 1. Typical graphs showing the manner in which velocity and elastic constants change with temperature are shown in Figures 5 and 6.

Discussion

The elastic constants determined by ultrasonic pulses are summarized in Table 2 which also contains the values published by Laquer, McGee, and Kilpatrick⁴ (referred to

³ J.J. Katz and E. Rabinowitch, The Chemistry of Uranium, 1951, p.137
⁴ H.L. Laquer, W.E. McGee, M.F. Kilpatrick, Trans. Am. Soc. Metals, 42:771 (1950)

subsequently as LMK) which were obtained by exciting longitudinal and torsional modes in smaller bars.

Young's Modulus is greatest for the beta treated specimens, but is less by about 15% at 300°C for both alpha and beta specimens.

For the single alpha bar examined in the static compression test Young's Modulus was found to be 15.8×10^{11} dynes/cm². The stress level, 1.7×10^8 dynes/cm², reached in the static test was relatively small. A modulus determined from the first longitudinal mode of vibration (7530 cycles per second for the 8 inch bars) yields a value, 17.6×10^{11} dynes/cm², intermediate to the values found by the ultrasonic and static compression tests. These variations can probably be attributed to inelastic behavior of the uranium.

The information on shear wave velocity is obtained directly from the torsional vibrations in the work of LMK while the shear data for this report is derived indirectly from subsidiary arrival times².

For the method of LMK it is assumed that the shear wave fronts are in a plane normal to the bar axis and move in a direction parallel to the axis. To interpret the oscillograms obtained by the HPM technique the shear waves are presumed to travel diagonally across the bar so that the wave front is conical in shape. Where elastic anisotropy is present this may lead to a different shear velocity than would prevail if the wave front were normal to the bar axis. Considering these differences in procedure it is somewhat surprising that data from the two methods agree as well as they do. Of particular interest is the change in Young's Modulus with temperature, $\frac{1}{E} \left(\frac{dE}{dT} \right)$. For alpha type bars the two methods yield practically the same results, $5.0 \times 10^{-4}/^{\circ}\text{C}$, decreasing with increase in temperature. The value obtained by LMK was for a small temperature change near room temperature while the NRL values cited in Table 2 are an average over the range from 25°C to 300°C. The change in modulus with temperature for beta treated bars is somewhat larger than for untreated material.

None of these data have taken into account the effects of neutron bombardment. Dienes' calculations⁵ indicate that irradiation effects can be of important magnitudes. Furthermore

⁵ G. J. Dienes, Phys. Rev. 86:228(1952)

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the direction in which the elastic constants are changed is dependent upon the type of collision process involved. A continuation of the ultrasonic investigation upon material within a pile or recently irradiated would be a natural extension of this study.

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Table 1
Description of Specimens

Bar No.	Diameter (inches)	Length (inches)	Remarks
<u>Group A</u>			
3077-F-21	0.9877 $\pm$.0001	8.06	No metal- lurgical data available.
<u>Group B</u>			
2896-1-1(α)	0.936 $\pm$.002	8.07	Heat treated at 600°C 1/2 hour.
2892-4-1(α)	0.993 $\pm$.001	8.09	Heat treated at 600°C 1/2 hour.
2896-2-27(β)	0.9904 $\pm$.0003	8.06	Heat treated at 720°C 70 seconds.
6339-B-22(β)	0.988 $\pm$.001	8.05	Heat treated at 720°C 70 seconds.
<u>Group C</u> (12 bars, 4 in each temperature class)			
4D621-A 630°C	0.9270 $\pm$.0002	8.00	Rough rolled to 1-1/2" dia. at 600°C. Finish rol- led at 630°C to 1" dia. then ground.
4D621-C 550°C	0.9270 $\pm$.0002	8.00	Finish rolled at 550°C to 1" dia. then ground.
4D621-C 480°C	0.9270 $\pm$.0002	8.00	Finish rolled at 480°C to 1" dia. then ground

//

Table 2
Summary of Elastic Constant Data Obtained by Ultrasonic Techniques

Specimen	Young's Modulus		Shear Modulus		Long.Velocity		Shear Velocity		Poisson Ratio		Coef.Lin. Expansion	$\frac{1}{E} \frac{dE}{dt}$
	$\frac{25^{\circ}\text{C}}{(10^{11}\text{dynes/cm}^2)}$	$\frac{300^{\circ}\text{C}}{(10^{11}\text{dynes/cm}^2)}$	$\frac{25^{\circ}\text{C}}{(10^{11}\text{dynes/cm}^2)}$	$\frac{300^{\circ}\text{C}}{(10^{11}\text{dynes/cm}^2)}$	$\frac{25^{\circ}\text{C}}{(10^5\text{cm/sec})}$	$\frac{300^{\circ}\text{C}}{(10^5\text{cm/sec})}$	$\frac{25^{\circ}\text{C}}{(10^5\text{cm/sec})}$	$\frac{300^{\circ}\text{C}}{(10^5\text{cm/sec})}$	$\frac{25^{\circ}\text{C}}{(10^{-6}/^{\circ}\text{C})}$	$\frac{300^{\circ}\text{C}}{(10^{-6}/^{\circ}\text{C})}$	$\frac{25^{\circ}\text{C}-300^{\circ}\text{C}}{(10^{-6}/^{\circ}\text{C})}$	$\frac{25^{\circ}\text{C}-300^{\circ}\text{C}}{(10^{-4}/^{\circ}\text{C})}$
<u>Group A</u>												
3077-F-21	18.6	16.1	7.91	6.63	3.28	3.16	2.05	1.89	.177	.223	13.7	4.9
	17.6*	-							-	-		
	15.8**	-							.216*	-		
<u>Group B</u>												
2892-4-1	18.1	15.6	7.62	6.27	3.28	3.12	2.02	1.85	.194	.237	11.1	5.0
2896-1-1	18.2	15.5	7.69	6.30	3.28	3.16	2.04	1.86	.188	.237	10.9	5.4
2896-2-27	19.3	16.3	8.22	6.57	3.35	3.20	2.10	1.89	.178	.232	15.9	5.6
6339-B-22	20.1	16.6	8.48	6.73	3.44	3.27	2.12	1.90	.194	.239	17.7	6.3
<u>Group C</u>												
4D621- 630°C	18.9	16.3	7.90	6.55	3.32	3.19	2.05	1.88	.190	.229	9.5	5.0
550°C	18.5	15.8	7.53	6.43	3.30	3.17	2.00	1.85	.205	.242	9.9	5.3
480°C	18.2	15.7	7.60	6.34	3.27	3.15	2.01	1.85	.195	.235	10.3	5.0
<u>LMK (ref.4)</u> <u>(average)</u>	20.5	-	8.34	-	3.29	-	2.09	-	0.23	-	-	5.0

* first longitudinal mode (7530 cycles per second) using method of LMK.
** static test in compression.

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FIGURE 1

LONGITUDINAL PULSE TRANSMISSION ALONG AXIS OF BAR
No. 2892-4-1, AN ALPHA SPECIMEN ANNEALED AT 600°C
FOR 1/2 HR.

FIGURE 2

LONGITUDINAL PULSE TRANSMISSION ALONG AXIS OF BAR
No. 6339-B-22, A BETA TREATED SPECIMEN ANNEALED AT
720°C FOR 70 SEC.

FIGURE 3 SPECIMEN HOLDER FOR ELEVATED TEMPERATURE MEASUREMENTS OF ELASTIC CONSTANTS.

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FIGURE 4 FURNACE FOR HEATING ULTRA-SONIC TEST SPECIMENS.

FIGURE 5

LONGITUDINAL AND SHEAR VELOCITIES AS A FUNCTION OF TEMPERATURE FOR SPECIMENS ROLLED AT VARIOUS TEMPERATURES.

FIGURE 6 YOUNG'S MODULUS AND POISSON'S RATIO AS A FUNCTION OF TEMPERATURE FOR SPECIMENS ROLLED AT VARIOUS TEMPERATURES.