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IS-400

Metals, Ceramics and Materials (UC-25)
TID 4500, December 15, 1960

UNITED STATES ATOMIC ENERGY COMMISSION

Research and Development Report

EFFECTS OF TEMPERATURE ON
MECHANICAL PROPERTIES OF
NORMAL URANIUM DINGOT

by

Knud Pedersen and Glenn Murphy

January 1962

Ames Laboratory
at
Iowa State University of Science and Technology
F. H. Spedding, Director
Contract W-7405 eng-82

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Printed in USA. Price \$.50 . Available from the

Office of Technical Services
U. S. Department of Commerce
Washington 25, D. C.

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EFFECTS OF TEMPERATURE ON MECHANICAL PROPERTIES OF NORMAL URANIUM DINGOT

Knud Pedersen and Glenn Murphy

ABSTRACT

Fatigue properties of normal uranium dingot for rotating beam specimens between 150 and 600°C are shown as S - N diagrams, and are also given by an empirical equation of the form $S = bN^m$, where S is the stress, N the number of cycles and b and m temperature dependent parameters.

Tensile properties for temperatures ranging from 30 to 700°C are presented in tabular form and as stress-strain diagrams.

All of the properties were found to decrease in value with increasing temperature except that at about 350°C they showed some irregularities. These irregularities can possibly be explained by the fact that at lower temperatures deformation by twinning predominates while slipping predominates above 350°C.

INTRODUCTION

Values of the yield strength (0.2% offset), tensile strength and modulus of elasticity for normal uranium dingot were determined at temperatures

ranging from 30 to 700°C, and fatigue properties were evaluated at temperatures from 150 to 600°C.

Because of the poorly defined proportional limit exhibited by uranium, special methods were employed to evaluate the modulus of elasticity and the yield strength. The fatigue tests were carried out at relatively low stresses, largely below the yield strength, in order to determine the maximum stress at which the material would not fail for 500,000,000 stress reversals.

Uranium has a high affinity for oxygen, especially at elevated temperatures; for this reason precautions were taken to protect the test specimens from the atmosphere during the tests. Using an inert atmosphere or a very low pressure for atmospheric protection closely resembles the actual conditions imposed on uranium in practical use because it is then either alloyed with other elements or it is enclosed in a casing of some corrosion-resistant metal.

Most of the data obtained are presented in the form of graphs; however, an empirical relationship was found for the number of cycles of completely reversed bending which a specimen may endure before failure as a function of the stress and temperature of the specimen.

OBJECTIVES

The mechanical properties of uranium depend upon its composition and structure and upon the environment. These factors are often expressed in terms of impurity content, grain size and orientation, fabrication pro-

cedure, previous working history, testing procedure and testing temperature. The effects of these factors are not yet understood sufficiently well to make possible accurate analytical predictions of properties. However, studies of the influence of each variable will develop information from which generalizations may be deduced.

The objective of the study reported here was to evaluate the effect of temperature upon some of the mechanical properties of normal uranium dingot.

MATERIAL

The material used in the tests was normal uranium dingot manufactured by the Mallinckrodt Chemical Works. The uranium was prepared by reduction from the salt with magnesium to a 3,400-lb dingot. The dingot was gamma extruded to a 7-in. diameter round which was then heat treated in a salt bath for 30 min at 1200°F and alpha extruded to rods approximately 1 3/8 in. in diameter. It was received as slugs 1 3/8 in. in diameter by 8 in. long.

The slugs were first cut into 4-in. lengths and were then sawed into quarters by cutting along two perpendicular diameters. The pieces obtained in this manner were then machined to the specimen specifications. By dividing the slug in this manner the specimens were all made from material equidistant from the surface and therefore with the same average grain structure, which was important because the material was not annealed before testing.

An analysis of impurity content is given in Table I.

Table I
Impurity Content of Test Material

	Mn	B	Mg	Ni	Cr	N	H	C	Fe	Si
PPM	<10	<0.10	<10	14	<5	12	1.3	20		
wt. %									.0053	.0027

The density of the material at room temperature was 19.03 gm/cm^3 .

EXPERIMENTAL PROCEDURE AND APPARATUS

Specimen Preparation

Fatigue Specimens. The 4-in. long segments which resulted from sectioning the slugs were centerbored in each end, placed between centers on a lathe and turned to an outside diameter of 0.466 ± 0.0005 in. When the entire batch had been turned, a motor driven turntable was mounted on the cross feed of the lathe for turning the fillet. A tool holder was fastened to the turntable, and an interchangeable carbide tip was fastened in the tool holder with the distance from the cutting surface to the center of the table held at $2 \frac{1}{2}$ in. A reverse switch on the motor for the turntable made it possible to take a pass in one direction, change the rotation of the tool, advance the feed and take a pass in the opposite direction.

The carbide tips used in the tool holder were triangular with a slight round on each corner so that when one cutting surface became dull a rotation of the tip in the holder would provide a new cutting surface. By using the motor driven turntable and a standard feed rate, the specimens

were all given the same amount of cold-work history, and by giving the last passes before the finish pass an advance of 0.001 in. the cold-work was kept to a minimum on the surface of the test specimen. A drawing of a fatigue specimen is shown in Fig. 1.

After machining, the specimens were again placed between centers on a lathe. A cloth-covered 5-in. diameter aluminum disk, attached to an electric drill mounted on the cross feed, was used for the polishing operation. Three steps were used in polishing starting with a 600 grit silicon carbide paper, going through 15 μ synthetic sapphire and finishing with 0.3 μ synthetic sapphire.

Both the specimen and the polishing disk were rotated, and the speeds were so adjusted that the abrasive was incident at approximately 45° to the center line of the specimen; at intervals the rotation of the specimen was reversed so that the abrasive would be incident approximately 45° on the other side of the center line. In this manner any circumferential pattern was eliminated.

Tensile Specimens. The tensile specimens were machined from a quarter slug to the specifications shown in Fig. 1. The threads were cut on the lathe immediately after rough turning, and the test section was machined last, again using interchangeable carbide tips and with a 0.001-in. advance being used on the last few passes before the finish pass. The tool was fed very slowly to minimize the amount of cold-work and to give a smooth finish. No polishing was employed on the specimen after machining.

TENSILE SPECIMEN

FATIGUE SPECIMEN

Fig. 1 - Dimensions of Specimens.

Testing Equipment

Fatigue. The fatigue specimens were encapsulated^{4, 7} in a flexible type 310 stainless steel, 0.018-in. wall tube, which was welded around the specimens inside a chamber first evacuated to approximately 4μ of mercury and then filled with argon gas for support of the arc.

The encapsulation procedure consisted of pressing two tubes, flared on one end and closed on the other end by a cap welded in place, onto the straight portions of the fatigue specimen with a section of stainless steel bellows placed between the two flared ends covering the test section of the specimen. The press fit between the tube and specimen was 0.002-in. diameter. The bellows were welded to the flares in the argon chamber and allowed the specimen to flex without a significant resistance being developed by the capsule providing an inert atmosphere for the specimen during the test. Sectional views of the steps used in the procedure are shown in Fig. 2.

The fatigue machines were of the rotating, simply supported beam type with a constant moment and no shear along the test section. An electric furnace with a temperature regulator provided an essentially constant temperature. To eliminate torque in the specimen due to bearing friction, electric motors were driving each end.

The ratio of the resisting moment of the stainless steel capsule used for protection of the specimens to the resisting moment of the specimen is equal to the ratio of the stiffness, EI , of the capsule to the stiffness of the specimen. The stiffness, EI (modulus of elasticity times moment of inertia with respect to a diameter) of the capsule was evaluated by suspending the

Fig. 2- Encapsulation of Fatigue Specimens. (a) Elements of Capsule, (b) Longitudinal Section of Empty Capsule, (c) Longitudinal Section of Capsule and Specimen, (d) Completed Capsule.

empty capsule as a cantilever, measuring the deflection as a function of load and evaluating EI by well established methods. It was found that the resisting moments of the capsules were 0.014% of the resisting moments of the specimens. Therefore, the resisting moment of the capsule was disregarded in calculating stresses in the specimens.

The tensile stress which resulted from expansion of the argon gas under high temperature was calculated by Bohn⁴ to be a maximum of 380 psi and was neglected. Pressing the stainless tubing onto the specimen created a compressive stress of short duration and low magnitude,⁴ and was not assumed to change the properties of the material.

Before a test was started at a particular temperature the furnace was calibrated while the machine was running with a dummy specimen by inserting a thermocouple next to the specimen and connecting the thermocouple to a room temperature compensated strip chart recorder and by regulating the controls until no temperature deviations were observed during an overnight period. Frequent checks were also made on the strip chart recorder with a thermometer and a Wheatstone bridge.

Next, by using two halves of a specimen, the machine was balanced for a no-load condition by observing the alignment of the two specimen halves through a telescope while adding or subtracting lead shot to the weight pans. This operation was also performed while the machine was running.

The machines were constructed with a microswitch that would turn off the motors and furnace at a given amount of strain of the specimen or when the specimen failed. A revolution counter recorded the number of cycles

from the instant the moment was applied to the specimen until the machine shut off.

Tension. The tensile tests were performed on a 60,000-lb Baldwin-Southwark hydraulic testing machine which was modified so that the pressure around the tensile specimen could be lowered to between 1.0 and 5.0×10^{-6} mm Hg, and the temperature could be held constant at any desired magnitude between room and 900°C .² The strain was picked up by an LVDT connected through a linkage to the specimen, and the load likewise transferred to an LVDT connected to the Tate-Emery load indicator. The signals from the LVDT's were recorded simultaneously by a Mosley Autograf x-y recorder, giving directly the actual stress-strain plot of the tensile test.

RESULTS

Fatigue. Figures 3 through 7 show conventional S-N diagrams in which the stress is calculated from $S = \frac{Mc}{I}$. Each point on the curve represents a test, and each curve represents a different test temperature.

Figure 8 shows a logarithmic plot of all of the data. A series of straight lines may be fitted to the points at a given temperature. The slopes and intercepts of the lines are listed in Table II and shown plotted against temperature in Fig. 9. It can be seen from the figures that the fatigue strength of uranium decreases steadily with increasing temperature except for a sharp discontinuity in slope and intercept occurring

Fig. 3 - S-N Curve of Uranium Dingot at 150°C.

Fig. 4 - S-N Curve of Uranium Dingot at 300°C.

Fig. 5 - S-N Curve of Uranium Dingot at 400°C.

Fig. 6 - S-N Curve of Uranium Dingot at 500°C.

Fig. 7 - S-N Curve of Uranium Dingot at 600°C.

Fig. 8 - S-N Curves of Uranium Dingot at All Test Temperatures.

Table II

Parameters for S-N Diagrams at Various Temperatures

Temperature °C	Slope m	Intercept	
		ln b	b (ksi)
150	-0.0633	10.87	52.6
300	-0.1405	11.57	106
400	-0.1125	10.96	57.6
500	-0.1271	10.86	52.1
600	-0.1434	10.79	48.5

at approximately 325°C. This discontinuity was also found for the endurance limit (Fig. 17) and modulus of elasticity (Fig. 16) and has been reported by other observers for many properties.⁵

It was evident that no simple equation could be found for the curves in Fig. 9, and it was assumed that a straight line relationship existed with the exception of the humps occurring at approximately 300°C. Equations for the slope and intercept were found by using the points at 150, 500 and 600°C as:

$$\text{Slope} = -(1.79)(10^{-4})t - 0.0367,$$

and

$$\text{Intercept} = \exp[-(1.39)(10^{-4})t + 10.90],$$

where t is temperature °C. By substituting these two equations in the general equation, $\ln S = m \ln N + \ln b$, the result is $\ln S = -[(1.79)(10^{-4})t + 0.0367] \ln N - (1.39)(10^{-4})t + 10.90$ which when rearranged becomes

Fig. 9 - Temperature Dependent Parameters of S-N Curves.

$$\ln N = \frac{10.90 - (1.39)(10^{-4})t - \ln S}{(1.79)(10^{-4})t + 0.0367} \quad \text{where}$$

N = number of cycles of completely reversed stress before failure,

t = temperature °C,

S = flexural stress in psi calculated from the conventional $S = Mc/I$.

If the small slope of the intercept line in Fig. 9 is neglected and the average value of 10.87 is used the equation for the number of cycles becomes

$$\ln N = \frac{10.87 - \ln S}{1.79 \times 10^{-4}t + 0.0367}$$

or

$$S = 52.6N^{-(0.000179t + 0.0367)} \text{ ksi}$$

The equation can be used to predict the fatigue life from 5×10^4 cycles to 5×10^8 cycles at temperatures up to 600°C except for the range between 200 and 400°C. Conventionally, the endurance limit is evaluated as the maximum stress that may be applied for 5×10^8 cycles without failure. It may be calculated as $S_e = (52.6) [(5)(10^8)]^{-(0.000179t + 0.0367)}$ in which S_e denotes the endurance limit in ksi.

Tensile. All tensile tests were made as closely as possible at the same strain rate (approximately 0.025 min^{-1}).

Figures 10 through 12 show samples of the Mosley Autograf x-y recordings of stress vs strain, and Fig. 13 shows a plot of the stress-strain diagrams at the different test temperatures.

In Figs. 14 and 15 stress-strain diagrams at 150 and 300°C are repeated across the sheet. They illustrate the effect that strain hardening

Fig. 10 - Stress-Strain Recording of Uranium Dingot at 30°C.

Fig. 11 - Stress-Strain Recording of Uranium Dingot at 150°C.

Fig. 12 - Stress-Strain Recording of Uranium Dingo at 700°C.

Fig. 13 - Stress-Strain Curves of Uranium Dingot at All Test Temperatures.

Fig. 14 - Repeated Loading Recordings of Uranium Dingot at 150°C.

Fig. 15 - Repeated Loading Recordings of Uranium Dingot at 300°C.

has on the proportional limit. In the first loading, curvature starts at zero strain, and the material exhibits almost no proportionality; however, as the total strain increases the proportional limit also increases, while the modulus of elasticity remains essentially constant.

The modulus of elasticity was found at each temperature by averaging the moduli of all the tests made at that particular temperature.

The tensile strength was found either by the position of the maximum hand on the load indicator at the end of the test or from the Autograf recording if this extended through the maximum.

Figure 16 shows a plot of modulus of elasticity vs temperature with the curve going through the averages and the range of values indicated by vertical bars. Again it is evident that there is a discontinuity near 325°C as was the case with the fatigue properties.

At 700°C the modulus of elasticity was taken from the ordinary tensile test rather than from a cyclic test and its value is therefore doubtful; it is clear, however, that an increase in the modulus of elasticity did take place between 680 and 700°C , which indicates that a minimum occurred at approximately the alpha to beta transformation temperature (666°C).

Figure 17 shows yield strength and tensile strength as a function of temperature, and while no tensile tests were run between 600 and 700°C it still appears that minima occurred near the transformation temperature, which is in accordance with results obtained by other observers.¹

Fig. 16 - Modulus of Elasticity as a Function of Temperature for Uranium Dingot.

Fig. 17 - Yield Strength, Tensile Strength and Endurance Limit as Functions of Temperature for Uranium DINGOT.

A summary of the properties and characteristics found for normal uranium dingot at different temperatures is given in Table III.

Table III

Properties of Normal Uranium Dingot at Different Temperatures

Temperature °C	Modulus of Elasticity psi x 10 ⁶	Tensile Strength ksi	Yield Strength ksi	Endurance Limit (5.0)(10 ⁸) cycles ksi
30	23.4	123.5	44.5	--
150	22.9	91.0	42.5	14.6
300	25.6	67.7	37.8	6.5
400	24.2	49.9	33.5	6.0
500	19.8	30.9	22.5	4.1
600	11.2	11.5	9.5	2.8
650	7.1	--	--	--
680	3.43	--	--	--
700	4.8	14.9	12.9	--
800	--	0.4	--	--

DISCUSSION OF RESULTS

The stresses calculated for the fatigue specimens are the engineering stresses as usually calculated. That is, they represent the stresses based on elastic theory and at the beginning of the test when the total cross section of the specimen contributes to the resisting moment. As the cross section of the specimen becomes smaller due to the formation of fatigue cracks the

stress increases correspondingly, and as yield occurs the stresses decrease at the outer sections and increase near the center. However, the method used here serves as a useful means of predicting the life of a fatigue specimen based on the initial conditions.

It was not possible to correlate the fatigue and tensile data by extrapolating the fatigue data to a half cycle; this can probably be explained by the difference in the two types of failure. The energy necessary to produce a dislocation is independent of the method of load application; however, because in fatigue the energy is supplied at a much slower rate, it is possible that this allows part of the dislocations to anneal. Further evidence of this is seen in Fig. 17 where the curve showing endurance limit vs temperature decreases in slope with increasing temperature, whereas the curve showing yield strength vs temperature increases in slope with increasing temperature indicating that annealing of the dislocations makes up for the reduction in strength at higher temperatures.

Another reason why no correlation could be obtained was that the fatigue tests were all carried out at relatively low stresses, most of them less than the yield strength, and the fatigue data given here apply only between $(5)(10^4)$ and $(5)(10^8)$ cycles. In Fig. 8 a few points may be seen at less than $(5)(10^4)$ cycles, and it is evident that these do not fall on the curves.

Figure 18 shows that the average grain size of a specimen tested at 150°C and of one tested at 600°C is approximately the same (about 0.0002-in. diameter), which indicates that the amount of grain growth has been small.

a **b** **c**

Fig. 18 - Photomicrographs of Uranium Dingot (a) before Testing, (b) after Testing at 150° C, 14,089 psi for 500 Million Cycles, (c) after Testing at 600° C, 6,038 psi for 500 Million Cycles.

This may have been due to the impurities which, if finely dispersed, will retard grain growth at annealing temperatures up to 575°C. At temperatures above 600°C the impurities coalesce and permit grain growth.⁶

Twin bands are much more numerous in the grains of the 150°C specimen than in the 600°C specimen which is to be expected since deformation by twinning predominates up to about 350°C after which slipping predominates. This is offered as an explanation of the discontinuities of the properties found around 350°C.

CONCLUSION

Endurance limit, tensile strength and yield strength of normal uranium ingot decrease with increasing temperature, but the effect of temperature on the endurance limit is smaller at high temperatures indicating that annealing takes place. The tensile strength and yield strength increase somewhat at the alpha to beta transformation temperature.

The modulus of elasticity decreases slightly from room temperature up to 150°C and then increases up to a maximum at about 325°C. From 325°C it at first decreases slowly until at 500°C it falls off rapidly at an almost linear rate until the transformation temperature has been reached. From one reading taken at 700°C it appears that the minimum modulus of elasticity occurs at the transformation temperature.

The relationship between stress and number of cycles to failure can be expressed by $S = bN^m$, where m , the slope, and $\ln b$, the intercept, vary linearly with temperature except for the range between 200 and 400°C where sharp discontinuities exist.

The endurance limit, defined as the maximum fully reversed stress which can be applied $(5)(10^8)$ times, can be expressed in the form

$S_e = e^{at + c}$, where t is the temperature and a and c are constants.

Elimination of the corrosive effects of the atmosphere by encapsulation of the specimens made it possible to obtain S-N diagrams with very little scatter and thus carry out the tests with a limited number of specimens.

Although moduli of elasticity obtained from tensile tests are not usually considered accurate for materials with a low proportional limit, it is felt that the method used here of raising the proportional limit by repeated loading and using a direct recording of stress and strain with large amplification has given dependable and consistent values.

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