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Research and Development Report

INFLUENCE OF RATE OF LOADING ON
THE TENSILE PROPERTIES OF
NORMAL ALPHA URANIUM

of
by

Philip Arthur Loretan and Glenn Murphy

August, 1963

Ames Laboratory

at

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INFLUENCE OF RATE OF LOADING ON
THE TENSILE PROPERTIES OF
NORMAL ALPHA URANIUM*

Philip A. Loretan and Glenn Murphy

ABSTRACT

Forty tensile tests were carried out on normal alpha uranium in order to determine the influence of the rate of loading and temperature on its tensile properties. These tests were conducted at eleven different temperatures in the temperature range from 25 to 600°C for three constant loading rates (0.0017 min^{-1} , 0.0130 min^{-1} , and 0.0400 min^{-1}). The properties considered were tensile strength, per cent elongation (in 1.5 in. gage length), percentage reduction in area, yield strength, and modulus of elasticity. All of these properties were more strongly affected by a change in temperature than they were by a change in rate of loading. Graphs showing data for each of the five properties vs temperature and also as a function of rate of loading are displayed to indicate specific effects. Original stress-strain curves included along with graphs indicating the slopes of each of these curves (subsequent to the initial elastic strain portion) as a function of temperature and rate of loading.

*This report is based on an M. S. thesis submitted by Philip A. Loretan to Iowa State University, Ames, Iowa, August, 1963.

INTRODUCTION

A number of experimental analyses have been conducted on uranium because of the usefulness of the material. Several investigators have even gathered extensive data in order to establish the tensile properties of uranium. However, as far as can be found in the literature, no one has ever tried to observe the influence that the rate of loading has on the tensile or mechanical properties of uranium.

The author became interested in the subject as a result of work he had carried out on the flexural creep properties of uranium. Initially, he wondered whether or not the short-time tensile test could be used to predict the flexural creep stress in a beam. For plastic flow, the equation $\epsilon = A\sigma^m |\dot{\epsilon}|^n T$ relating stress (σ) to plastic strain (ϵ), strain rate ($\dot{\epsilon}$) and temperature (T) with the constant A , seems to hold well for uranium in a short-time tensile test. Thus, it was felt that it might be possible to utilize m , the slope of the stress versus strain curve on log paper, to predict the stress in a beam at any position, for any temperature. To do so, one would utilize the derived flexural creep formula,

$$\sigma_y = \left[\frac{Mh}{2I} \left(\frac{2y}{h} \right)^{\frac{1}{m}} \left(\frac{2m+1}{3m} \right) \right]$$
 where m is normally the slope taken from a tensile creep test. In this formula, σ_y is the stress at the distance y from the neutral axis of the beam, M is the bending moment, h is the y distance at the outer

edge of the beam and I is the moment of inertia. If m is found to be the same for a short time tensile test as it is during a tensile creep test, then using the slope from either test would be considered valid in the aforementioned formula. Of course, a short-time tensile test is much more easily performed and this is where the advantage is apparent. However, since a low strain rate during a short-time tensile test can be classified as a creep test (1), the interest will lie in what happens when the rate is increased. If the higher rate of loading changes the slope considerably at a given temperature, one would in that case, not be permitted to interchange m 's. However, if the slope does not change appreciably, then one could validly use the slope found at any rate of loading. Thus, a principal objective of this analysis was to determine the effect of the rate of loading on the slope, ie. actually on the stress-strain curve.

So a single investigation prompted the analysis considered in this thesis but the results of the effort were of a broader nature. Not only were data collected on the tensile properties of normal alpha uranium but the work performed provided insight into twin and slip mechanisms of deformation in uranium and also strain hardening in that material.

REVIEW OF LITERATURE

Many reports on the investigations of the influence of the rate of loading on a wide variety of materials have been published. Rather than consider the publications on each material separately however, reports and articles were sought which principally considered the overall influence of the loading rate on several materials. Thus, the following reviews will be primarily oriented to such an approach.

Bernett (1) found that changes in the speed of testing, especially at higher temperatures, produced great differences in tensile and compressive strengths. His analysis of the mechanical properties of four metallic sheet materials were carried out at speeds from 0.00001 to 0.1 inch/inch/sec., at various temperatures. Some of his conclusions were

1. For limited amounts of strain, the compressive and tensile behavior of these materials is similar.
2. In evaluating both tensile and compressive strengths, the speed of testing, ie. strain rate, is very important, particularly at high test temperatures.
3. The modulus of elasticity was insensitive to strain rate in all cases except at elevated temperatures on one particular material.
4. Creep at high temperatures and high stress levels is a critical factor both in tension and compression.

Results here indicate that large plastic deformations

can occur in a time interval of the order of a few seconds.

5. At high temperatures, creep rates can be roughly estimated from the tensile stress-strain curves, ie. at the stress level where the stress-strain curve is essentially horizontal, the creep rate is approximately equal to the tensile testing strain rate.

Moon and Campbell (2) have drawn stress versus strain rate plots from tensile data for many metals and alloys. The tests were performed at room temperature and also at elevated temperature for the purpose of illustrating the effects of increasing strain rates. They found the general trends of the analysis for each material were as follows:

1. At room temperature, yield and tensile strengths of the material either are not affected or are increased slightly with increasing strain rate.
2. At slightly elevated temperatures the effect is, in general, similar to that at room temperature, if the material has negligible tendency to creep at stresses lower than the yield strength and remains in a stable condition. However, the yield and tensile strengths are usually lower, dependent on temperature. Under these conditions, the length of time at which the specimen is maintained at the testing temperature before it is loaded has little effect on its strength.

3. At high temperatures, substantial increases are caused in yield and tensile strengths with increasing strain rate, if the material tends to creep at stresses lower than the yield strength. Yield and tensile strengths tend to coincide for a given material as testing temperature is increased.
4. At a given temperature, the elastic modulus of a material is relatively constant regardless of strain rate.
5. Effects of strain rate on ductility are not constant.
6. Reactions which change the structure of the material will affect its properties when it is heated to a temperature at which the reaction can proceed. The reactions considered may be precipitation hardening, strain aging, overaging, tempering, recrystallization, and grain growth, or other reactions or combinations of them.

Steidel and Makerov (3) used static strain rates of 10^{-5} , 10^{-4} and 10^{-2} inch/inch/sec. on the engineering materials with which they worked. All the materials showed an increase in yield strength and tensile strength with strain rate increases. Most of the materials displayed an increase in elongation at fracture with increased strain rate. The per cent reduction in area was found to be greater as strain rate increases for the majority of materials tested also.

Davis (4) found that plots of stress and yield point elongation as functions of the rate of loading, displaying ultimate strength, yield point and yield point elongation are definitely influenced by the rate of loading. The effect is very noticeable especially at the faster rates.

He further stated that since stress is a function of both strain and strain rate, an increase in stress may be caused by an increase in either the strain or the strain rate. Thus, the rate of strain hardening must be expressed by the partial derivative $\frac{\partial \sigma}{\partial \dot{\epsilon}}$ instead of the general expression $\frac{d\sigma}{d\epsilon}$.

Morrison (5) worked principally with steels. His results indicated that all the stress values tend to rise with increased speed of testing; however, the form of the stress-rate of strain curves differs. The value of the yield stress seemed to approach asymptotically, at low speeds, a definite minimum value, and rose very rapidly at the other end of the rate-of-strain scale. The plastic yield and ultimate stresses, on the other hand, seemed to suggest that the material, after yield, behaves like an extremely viscous fluid. These values did not increase so rapidly at high speeds, but they gave little indication of approaching a fixed minimum value at the lowest speeds used as was the case with the yield stress discussed above.

Jones and Moore (6) in their work on a number of metals found that the rate of strain had an appreciable effect on the tensile test data. However, with the exception of stain-

less steel specimens, the extent of this effect might be expressed by the statement that a variation of rate of strain from N per cent per minute to $2N$ would introduce a variation not greater than 1% in the value of the yield or the tensile strength and not greater than 3% in elongation or reduction of area.

Fry (7) performed over 300 tensile tests at various speeds on a number of testing machines to study how the rate of pulling affects the yield point and tensile strength at room temperature. He observed that the tensile strength was not greatly influenced by the strain rate but that there was a considerable effect on the yield point. His general conclusions were

1. Yield point values determined under normal testing conditions show a scatter considerably greater than can be attributed to variations in the quality of the material.
2. Yield point values tend to increase with an increase in the rate at which the test specimen is strained.
3. Yield point values increase generally in a straight-line relation with the logarithm of the rate of straining. There is also some indication that for the same increase in the rate of straining, the rise in yield point is less rapid with specimens that have 8-inch gage lengths than it is with specimens

of 2-inch gage lengths.

Austin and Steidel (8) worked with a method to determine the dynamic tensile properties of materials at high strain rates. They found that for most engineering materials, dynamic strength increases with increasing strain rate and decreases with increasing temperature. Under adiabatic conditions of high-speed plastic deformation experienced in impact loading, the observation was that the effects of strain rate and temperature apparently act simultaneously.

Few experimenters have actually tried to relate the effect of strain rate to the other variables involved in tensile testing. However, Lubahn (9) has derived an equation relating stress (σ) for plastic flow, plastic strain (ϵ), strain rate ($\dot{\epsilon}$) and temperature (T). Three basic equations are utilized in the derivation.

$$\epsilon = A\sigma^m \Big| \dot{\epsilon}, T \quad (1)$$

$$\sigma = B\dot{\epsilon}^n \Big| \epsilon, T \quad (2)$$

$$B = T(F - \ln \dot{\epsilon}) \Big| \sigma, \epsilon \quad (3)$$

The general expression,

$$\sigma = C G^T (\dot{\epsilon}/\dot{\epsilon}_0)^{DT} \epsilon^{(E - FT \ln \dot{\epsilon}/\dot{\epsilon}_0)} \quad (4)$$

where C , D , E , F , G and $\dot{\epsilon}_0$ are constants of the material, was then developed from these relations.

OBJECTIVES OF THE INVESTIGATION

The paramount purpose of this investigation was to observe the effect which an increase in the rate of loading had on the tensile properties of normal alpha uranium. Three different constant strain rates were utilized in the analysis. Observations were then made on the tensile strength, elastic modulus, yield strength at 0.2% offset, percentage elongation (in 1.5 inch gage length), percentage reduction in area and slope of the stress versus strain curve in the region of plastic flow. From the data on these properties, some considerations on how the rate of loading affected strain hardening in uranium at different temperatures could be made. In addition, special characteristics of deformation by twinning and slip in uranium could be observed.

MATERIAL AND APPARATUS

It has been brought out by Hueschen (10) that the properties of uranium are sensitive to orientation, which is controlled by prior heat treatment and fabrication history. Such sensitivity to orientation is due to anisotropy, ie. the properties of uranium are dependent on the crystallographic direction in which the measurement is made.

It has further been reported by Hueschen (10) and also by Kaufmann (11, p. 65) that variations in chemical composition are known to have a marked effect on the mechanical or tensile properties of uranium.

Holden (12, p. 66) states that uranium, like many other metals, can have a wide variation in tensile properties depending on many factors such as grain size, preferred grain orientation, previous work history, impurity content, testing procedure and testing temperature.

So it becomes necessary to define the condition of the specimen being tested and the method of testing quite carefully, if the tensile properties are to have any meaning at all.

Material

Mallinckrodt Chemical Works manufactured the normal alpha uranium which was utilized in the tensile tests considered for this report. 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-inch diameter round which was then heat treated in a salt bath for 30 minutes at 1200°F and alpha extruded to rods approximately 1 3/8 inch in diameter. It was received as slugs 1 3/8 inch in diameter by 8 inches in length.

Analysis of the impurity content is given in Table 1.

Table 1. Spectrographic and chemical analysis of impurity content in test material as furnished by fabricator

Element	Mn	B	Mg	Ni	Cr	N	H	C	Fe	Si
PPM	<10	<0.10	<10	14	<5	12	1.3	20		
Wt. %									0.0053	0.0027

The density of the material at room temperature was 19.03 gm/cm³.

Specimen Preparation

None of the specimens were annealed before testing so it was important to prepare the specimens so that they would be as similar in grain structure as possible. This was done by first cutting the 8-inch slugs into 4-inch lengths. By cutting along two perpendicular diameters, each 4-inch slug was then sawed into quarters providing the rough pieces from which the specimens were subsequently machined. Therefore, every specimen had about the same average grain structure

since they were all made out of material equidistant from the surface of the slug.

The 4-inch specimen was prepared so that the reduced testing section at the center two inches of the specimen had a 0.357 inch diameter as recommended for tensile testing by the ASTM standards (13). The remainder of the specimen was threaded.

1/2 - 13UNC threads were cut approximately one inch long on each end of the specimen immediately after rough turning was completed and then the center 2-inch test section was machined. By means of interchangeable carbide tips and an advance of 0.001 inch, the 0.357 (+0.001, -0.000) inch specification was met in this test section of the specimen. A finish pass then gave the piece a smooth appearance.

The tool was fed very slowly for the duration of the machining of the specimen since uranium is spontaneously flammable at temperatures caused by fast machining and also in order to minimize the amount of cold work affecting the piece.

Testing Equipment

The tensile testing of uranium, especially at higher temperatures requires a unique testing facility since this material is easily oxidized (14). The equipment used in performing the tests for this report will be described briefly.

Much of the apparatus was specially designed by Bohn and Murphy (15).

Test facility

Load application for the tensile tests was provided by a 60,000-lb. Baldwin-Southwark hydraulic testing machine. This was used in conjunction with a Tate-Emery load indicator, an electronic proportioning furnace controller, a high temperature vacuum test chamber, an extensometer - LVDT strain indicator, a Mosley Autograf x-y recorder for load-strain recording, vacuum pumping and measuring instruments and temperature indicating and recording potentiometers. A platinum resistance thermometer, wound integrally with furnace heater windings, provided temperature sensing for control. Four chromel-alumel thermocouples attached to the specimen provided temperature measurements.

A specimen was set up in the total test assembly by first having it secured in the Baldwin testing machine. With extensometer and thermocouples attached, it was then enclosed in the vacuum system where it in turn underwent thorough heating by a furnace located outside the vacuum system. With the temperature set at the correct level as seen on the recorder, straining the specimen caused the extensometer-LVDT strain indicator to be activated. The strain and load indications then were plotted on the stress-strain coordinates of the Mosley Autograf x-y recorder and a record of the entire test

was obtained.

Test chamber

To provide protection against oxidation, a vacuum chamber, as mentioned above (15), housed the specimen and its extensometer mechanism. This chamber was attached by means of the lower load application rod to the lower stationary cross-head of the tensile machine and thus did not affect the tare weight of loading. During loading, elongation of the chamber was permitted by means of a bellows at the top of the chamber.

Pressures between 1 and 5×10^{-6} mm Hg could be realized by the pumping system which consists of a mechanical fore pump, an oil diffusion pump and a liquid nitrogen cooled cold trap. With pressures such as these, the furnace could go to temperatures up to 1000°C without oxidation effects on the uranium. Only chamber components, which were primarily 316 stainless steel prevented higher temperatures.

Extensometer - LVDT strain indicator

The testing system utilized a linear variable differential transformer (LVDT) to transfer strain measurements through the vacuum wall of the test chamber (15). The movable core of the LVDT is positioned on the inside of a flexible well of the vacuum chamber and the voltage developed as this core moves gives an indication of the strain in the specimen. Of course, the core motion occurs as a result of the movement

of the flexible well. By means of the well, the motion was transmitted from the knife edges that are rigidly attached to the tensile specimens. Thus, strain was actually read out through the LVDT. The ac output voltage of the LVDT was rectified to dc and both load (stress), from the Tate Emery indicator, and strain could be sensed and plotted on the Mosley Autograf recorder.

EXPERIMENTAL PROCEDURE AND RESULTS

In order to carry out a tensile test on normal alpha uranium, a specimen was set up with a 1.5-inch gage length between the knife edges in the apparatus previously described. Next, the vacuum system was started and when a sufficient vacuum had been achieved, the furnace was turned on. The specimen was then brought up to a predetermined temperature while the system was kept evacuated properly. When the desired temperature was achieved, as recorded from the thermocouple at the center of the specimen, the tensile test could finally be performed. Eleven different temperatures in the range from room temperature to 600°C were utilized (25°C, 80°C, 150°C, 200°C, 250°C, 300°C, 350°C, 400°C, 500°C, 550°C and 600°C). Three different constant rates of straining were also employed at each temperature (0.0400 min.^{-1} , 0.0130 min.^{-1} and 0.0017 min.^{-1}). To maintain these rates, the operator adjusted the Baldwin machine properly over intervals. Forty tensile tests were carried out but some data on several tests were disregarded because of inoperation of some part of the apparatus.

The results of each of the forty tensile tests are reported in Table 2. The temperatures shown in this table were those listed on the temperature recorder. Such temperatures were therefore registered at the center of the specimens.

Table 2. Tensile properties of normal alpha uranium

Test no.	Temp. (°C)	Strain rate (min ⁻¹)	Tensile strength (ksi)	Percentage elongation in 1.5 inch gage length	Percentage reduction in area	1/m	Modulus of elasticity (psi x 10 ⁶)	Yield strength at 0.2% offset (ksi)
1	25	0.0130	95.6	8.7	11.2	0.355	25.2	42.0
2	25	0.0400	98.2	6.7	9.1	0.299	27.5	40.5
3	25	0.0017	93.5	8.7	9.6	0.284		
4	80	0.0130	96.8	26.7	22.1	0.319		
5	80	0.0400	97.7	28.1	20.1	0.300	29.1	37.6
6	80	0.0017	95.1	18.0	15.0	0.306		
7	150	0.0130	74.8			0.239		
8	150	0.0017	78.4	27.3	29.3	0.301	20.8	31.7
9	150	0.0130	74.4	31.7	27.8	0.264		
10	150	0.0400	79.0	31.7	31.1	0.257	30.3	34.2
11	150	0.0130	74.6	27.7	37.6	0.253		
12	150	0.0017	76.5	29.5	29.3	0.232	27.5	34.7
13	200	0.0130	65.7	28.8	49.7	0.222	24.3	32.6
14	200	0.0400	65.2	31.1	48.5	0.246	26.3	31.6
15	200	0.0017	65.3	31.3	44.8	0.204	20.7	33.7
16	200	0.0400	64.2	29.6	37.6	0.230		
17	250	0.0130	52.0	28.7	52.4	0.198	21.7	30.2
18	250	0.0400	52.4	31.3	59.7	0.195	26.1	31.4
19	250	0.0400	55.2	28.3	52.0	0.223	24.4	29.9
20	250	0.0017	50.8	22.3	45.2	0.182	20.2	30.1

Table 2. (Continued)

Test no.	Temp. (°C)	Strain rate (min ⁻¹)	Tensile strength (ksi)	Percentage elongation in 1.5 inch gage length	Percentage reduction in area	1/m	Modulus of elasticity (psi x 10 ⁶)	Yield strength at 0.2% offset (ksi)
21	300	0.0130	47.2	31.3	50.1	0.193	17.9	30.4
22	300	0.0017	46.2	24.1	48.1	0.166	16.6	29.2
23	300	0.0400	47.6	30.8	57.3	0.143	22.6	32.6
24	350	0.0400	36.6	20.0	57.7	0.142	19.4	27.6
25	350	0.0130	37.4	25.7	59.1	0.153	22.0	27.0
26	350	0.0400	39.8	25.3	57.7			
27	350	0.0017	36.3	15.9	56.2	0.139	16.4	26.5
28	400	0.0130	33.7	22.6	63.0	0.149		
29	400	0.0400	31.6	20.0	56.2	0.123	17.4	26.5
30	400	0.0017	32.9	22.7	65.3	0.139	16.7	24.6
31	500	0.0130	16.3	29.9	74.5	0.103	15.4	13.8
32	500	0.0400	19.1	27.2	71.6	0.089	15.3	16.2
33	500	0.0017				0.094	10.7	10.8
34	500	0.0017	11.0	30.3	81.1	0.067	9.8	10.0
35	550	0.0400	10.2	34.1	83.7	0.089	15.5	10.4
36	550	0.0130	10.1		88.1	0.117	10.8	8.9
37	550	0.0017	8.3	36.1	92.6			
38	600	0.0400	6.0	48.0	92.4	0.177	9.5	4.5
39	600	0.0130	5.4	46.7	91.8	0.107	11.4	4.5
40	600	0.0017	4.1	44.0	81.8	0.091	13.5	3.2

The rate of loading was defined by that strain rate found in timing the progression of the x-y recorder as it plotted the stress-strain curve.

The tensile strength was determined by reading the maximum position of the hand on the load indicator. A plot of tensile strength versus temperature for the three different rates of loading is shown in Figure 1. Figure 2 displays tensile strength versus strain rate with temperature as the parameter.

Percentage elongation of a specimen for a 1.5-inch gage length was calculated by measuring the distance between the knife edge marks for the broken specimen and comparing this length to the original 1.5-inch gage length. Figure 3 displays plots of percentage elongation (in 1.5 inch gage length) versus temperature for the three rates of straining. Figure 4 then shows this percentage elongation as a function of strain rate for various temperatures up to 600°C.

The calculation of percentage reduction in area for the specimens was made from a measurement of the necked down area of the broken specimens as compared to the original cross-sectional area. If the necked down region of the broken specimen was oval-shaped, an average of the major and minor axes was used to find the reduced area. Of course, the original area of the test portion of the specimen was 0.1 square inch based on a 0.357 inch diameter. Figure 5 is a

Figure 1. Tensile strength as a function of temperature for three different rates of loading

Figure 2. Variation of tensile strength with rate of loading for temperatures from 25°C to 600°C

Figure 3. Percentage elongation as a function of temperature for three different rates of loading

Figure 4. Variation of percentage elongation with rate of loading for temperatures from 25°C to 600°C

a graph of percentage reduction in area versus temperature for the three rates of loading and Figure 6 is that same reduction versus strain rate for temperatures in the range of room temperature to 600°C.

By locating, on log paper, the straight line portion of the stress-strain curve which obeyed the formula $\epsilon = A \sigma^m$, m , or rather $1/m = \frac{\Delta \ln \sigma}{\Delta \ln \epsilon}$ can be calculated. $1/m$ versus temperature for the three rates of loading is shown in Figure 7. To illustrate the rate of loading influence, $1/m$ versus strain rate is plotted in Figure 8 for different temperatures which were considered.

Though it is very difficult to establish the modulus of elasticity from a stress-strain curve for uranium (10, 12, 16), since the initial portion of the curve is not linear, some approximate values were obtained. The values of the modulus were determined by calculating the slope of the straight line portion of the stress-strain curve. If the plot appeared to have any initial straight line portion at all, this was chosen to be used in the calculations. The values thus obtained were plotted versus temperature for each of the three rates of loading and can be seen in Figure 9. The modulus of elasticity versus strain rate plot in Figure 10 shows the influence of the rate of loading on the modulus values at selected temperatures.

Figure 5. Percentage reduction in area as a function of temperature for three different rates of loading

Figure 6. Variation of percentage reduction in area with rate of loading for temperatures from 25°C to 600°C

Figure 7. Slope of the stress-strain curve for plastic flow as a function of temperature for three different rates of loading

Figure 8. Variation of the stress-strain curve for plastic flow with the rate of loading for temperatures from 25°C to 600°C

Figure 9. Modulus of elasticity as a function of temperature for three different rates of loading

Figure 10. Variation of the modulus of elasticity with rate of loading for temperatures from 25°C to 600°C

The yield strength at 0.2% offset was located in each of the tests for which a modulus of elasticity had been determined. The yield strength was evaluated at 0.2% offset in order to be certain that the material had actually undergone permanent deformation and in accordance with ASTM specifications. Figure 11 is a graph of yield strength (0.2% offset) as a function of temperature for the three rates of loading. However, the rate of loading effect on the yield strength can be observed more clearly in Figure 12 where yield strength versus strain rate is plotted with temperature as the parameter.

Figures 13, 14 and 15 are log plots of stress versus strain with a parameter of temperature where each graph was plotted for a different rate of loading. The portion of the curves that obeys the formula $\epsilon = A \sigma^m$ is indicated in each of the figures.

A log plot of stress versus strain is presented in Figure 16 for temperatures in the 25°C to 600°C range and for certain definite strains at these temperatures.

Figures 17, 18 and 19 were drawn to display the original stress-strain curves out to a strain of 20×10^{-3} . Thus, they are the actual results of the experimental work. Each figure shows the curves for one particular rate of loading only, with temperature as a parameter.

Figures 20, 21 and 22 are graphs of stress versus strain

Figure 11. Yield strength as a function of temperature for three different rates of loading

Figure 12. Variation of the yield strength with rate of loading for temperatures from 25°C to 600°C

Figure 13. Log plot of stress versus strain for the lowest rate of loading at temperatures from 25°C to 600°C

Figure 14. Log plot of stress versus strain for the medium rate of loading at temperatures from 25°C to 600°C

Figure 15. Log plot of stress versus strain for the highest rate of loading at temperatures from 25°C to 600°C

Figure 16. Stress as a function of strain rate at certain strains for temperatures from 25°C to 600°C

Figure 17. Stress-strain curves over range of temperatures for lowest rate of loading

Figure 18. Stress-strain curves over range of temperatures for medium rate of loading

Figure 19. Stress-strain curves over range of temperatures for highest rate of loading

Figure 20. Stress-strain curves for various rates of loading at 150°C

Figure 21. Stress-strain curves for various rates of loading at 350°C

Figure 22. Stress-strain curves for various rates of loading at 550°C

where rate of loading is the parameter. These curves are also taken from the original stress-strain diagrams as indicated on the x-y recorder. Figure 20 is plotted for a temperature of 150°C, Figure 21 for 350°C and Figure 22 for 550°C.

Several typical original stress-strain curves have been placed in the Appendix for the purpose of illustration, but the important portion of these original curves has already been included in Figures 23, 24 and 25.

DISCUSSION OF RESULTS

As a result of the tensile tests which were performed on normal alpha uranium, the conclusion was made that the tensile properties of this material are affected by the rate of loading. However, the extent of the influence of the rate of loading is not nearly as great as the effect of temperature on the tensile properties. This should be obvious from a study of Figures 1 - 22. The specific properties displayed in these figures are discussed individually below.

The tensile strength of uranium decreases with increasing temperature as observed in Figure 1. Previous analyses on uranium (10, 12, 17, 18), have resulted in data which are generally comparable to this with the exception of the initial portion of the curve. Few experimenters have observed the anomaly in the region of 80°C for uranium because they have not considered it important to make a test between room temperature and 100°C. Thus, most tensile strength versus temperature curves do not show a deviation at this point. However, such an anomaly in uranium has been observed previously by Bernard and Coureau (19) and is significant since it seems to affect many of the tensile properties of the material at this temperature. The tensile strength of uranium is as high or higher, depending on the rate of loading, at 80°C as it is at 25°C (Figure 1). Above this temperature however, the

tensile strength decreases with increasing temperature as was previously mentioned.

It should be noted that the test with the lowest rate of loading appears to have the lowest tensile strength. This can be observed more clearly in Figure 2. An increase in rate of loading or strain rate generally causes an increase in tensile strength for any material considered, especially at higher temperatures (1, 3, 5).

There are several interesting areas to study in the curves of Figures 3 and 5. The percentage elongation of uranium, for all gage lengths, characteristically increases quickly before leveling off in its plot while the percentage reduction in area increases almost steadily (10, 12, 17, 19, 18). The reason that the curves take such shapes is rather easily explained. In the range near room temperature the deformation seems to be quite uniform over the entire reduced section of the specimen but as the temperature is increased, necking down occurs and the elongation is then localized more to the necked region. Thus, a definite break will occur in the elongation curve when localized necking down is initiated. However, the reduction of area plot will not be affected nearly as much since it is based on necking down of the specimen from the start.

So in the region of 60°C to 70°C, a brittle transition seems to take place in uranium (12, p. 109), as displayed on

the percentage elongation versus temperature curve. The material is much more brittle at room temperature than it is at higher temperatures. Holden (12, p. 109) adds that this transition temperature in uranium is a function of impurity content and that it also may be caused in part by the high stresses resulting from the twinning mode of deformation.

Since the subject has been introduced, it should be pointed out that twinning is certainly involved in the significant deviation from the smooth plot observed in the region of 350°C , in Figures 3 and 5. It has been known for a long time that at about 350°C , the principal form of deformation predominating in uranium shifts from twinning, which has been more active below this temperature, to slip (9, 12, 17). McLean (20, p. 88) brings out the point that the stress for twinning tends to be large at room temperature and below, with the result that twinning occurs under conditions where yield stress is high. For example, he states that twinning will be particularly large at low temperatures or high rates of strain in bcc metals. Uranium has orthorhombic symmetry and it can be considered as having a deformed hexagonal close-packed structure (21, 22), so it is certainly not bcc. However, one can not help notice that in Figure 3 and in Figure 5 also, the deviation from the smooth plot seemed to occur for the low rate of loading before it did for the others. Thus, twinning appears to give precedence to slip sooner at the low rate of

loading. The other two rates of loading are closer together and so one is unable to state definitely that twinning will tend to predominate longer at the higher rate of loading. The plot of reduction in area would substantiate such a statement however. So it is postulated that there is not only a temperature dependence on when slip plays the paramount role as a mechanism of deformation in uranium but also a rate of loading dependence.

One must remember however, as Nichols (16) and others have brought out, that not too much reliance should be put in graphs of percentage elongation or percentage reduction in area. Nichols stated that values he had seen reported for percentage elongation in uranium had ranged at room temperature from 5 - 15% and at 500°C, from 5 - 57%. Perhaps a good example of this would be to take Figures 4 and 6 and to try to state what the influence of rate of strain is in these plots. One could not say that there is definitely an increase or decrease in either percentage elongation or reduced area with increased rate of loading though the low rate of loading seems to present the lowest value for both, in the majority of cases.

The slope, $\frac{\Delta \ln \sigma}{\Delta \ln \epsilon} = 1/m$ of the stress-strain curve noticeably decreases as the temperature increases (Figure 7). Therefore, m in the formula $\epsilon = A\sigma^m$, for plastic flow, increases considerably with increasing temperature. This result

indicates that a much smaller stress is needed to cause a certain strain in uranium at a high temperature than is needed at a low temperature. The implication is that the amount or magnitude of strain hardening which uranium will undergo at a given strain rate becomes less as the temperature is increased.

Some significance may also be attributed to the fact that the region of validity of the formula, $\epsilon = A \sigma^m$ not only commences sooner but also becomes smaller and smaller as temperature increases (Figures 13, 14 and 15).

In considering a certain temperature, the variation of $\frac{\Delta \ln \sigma}{\Delta \ln \epsilon}$ as a function of strain rate (Figure 8) indicates that the degree of strain hardening is least for the lowest rate of loading. The influence of strain rate is nowhere near as great as the influence of temperature but it is still noticeable. With a low rate of loading, the material appears to have the opportunity to rearrange itself in some manner so that strain hardening does not occur to as great an extent as it does in the faster rates of loading.

As was mentioned in the previous section of this report, the modulus of elasticity and yield strength of uranium are difficult to determine. Nichols (16) found that the modulus of elasticity reportedly varied at room temperature from $15.8 - 30.0 \times 10^6$ psi. Nichols adds further that the proportional limit is even less well defined as the temperature increases and so problems become even greater. This is men-

tioned merely to precaution the reader on the use of the values of the elastic modulus. However, for both the properties of modulus of elasticity and yield strength, the curves agree quite nicely with reference values (17, 23). As functions of temperature, both properties decrease with increasing temperature and display the familiar variation from the smooth curve in the range of 350°C. The yield stress plot of Figure 11 illustrates the digression well but deviations from smooth plots in Figure 9 for the modulus of elasticity are quite apparent in this range also.

For the low rate of loading, several values of the modulus of elasticity are missing. The reason is, as a result of the shape of the stress-strain curve, an uncertainty exists in deciding what portion of the curve to use in order to calculate the modulus for the low strain rate. Therefore, where the curve had no initial linear region, no elastic modulus was determined. Actually one wonders whether these values are valid anyway since the low rate tensile test is almost a creep test. Bennett (1) stated that for the material he worked with, the lower values obtained at a very low strain rate are thought to be a result of the distortion of the stress-strain curve due to creep. Thus, he felt that these values really should not be utilized since the initial portion of the stress-strain curve does not seem to be elastic under conditions of very low strain rate and high temperature. How-

ever, the values for the modulus of elasticity are reported and one can observe the influence of the rate of loading on them in Figure 9. The modulus certainly increases with higher strain rates.

The influence of the rate of loading on the yield stress (Figure 12) can be taken as an indication of strain hardening. If the yield stress increases, this is taken to be a strong indication that the amount of strain hardening has increased. From Figure 12, one can see that even though the influence is small, there does appear to be an increase in yield stress with increasing strain rate, especially at the higher temperatures. Thus, once again it can be surmised that the degree of strain hardening in normal alpha uranium increases with an increase in the rate of loading.

Lubahn (9) in his derivation of a general flow equation in the region of plastic flow utilizes a basic equation for metals, as was cited in the literature review. $\dot{\epsilon} = A \sigma^m | \dot{\epsilon}, T$ (1) This formula applies to uranium in the regions as marked in the stress-strain curves of Figures 13, 14 and 15. One of the main reasons for including these log plots was to indicate how the portion of the curve, which equation 1 holds for, varies with temperature. As was previously mentioned, the left hand limit and also the extent of the region of validity both vary with temperature. The right hand limit of the region considered in the three figures was defined because of necking

down occurring in the specimen. The x-y recorder was not able to correct for this and thus the stress values decreased correspondingly resulting in incorrect data beyond this limit.

Equation 2 is found to be valid as a result of plots in Figure 16. There is one basic difficulty however in utilizing this equation and that has to do with the limited portion of the curve where such an equation will hold. It is valid only for plastic flow as was equation 1 and thus really should not be considered too near to the beginning of the test. Therefore, in order to be able to correlate this equation to equation 1 and still be in a valid region, a strain within the limits of the curve where equation 1 was valid has been taken. Thus, different strain values were used to ascertain the stress as the temperature increased. So even though equation 2 seems valid from the linear plot results of Figure 16, one could not correlate this equation along with equation 1 into one general flow equation since the regions of validity of the two equations vary with temperature. A general flow equation such as equation 4 is therefore impossible. A less general equation with specific validity regions for different temperatures however would be possible.

Holden (12, p. 66) indicates that it is very difficult to assess the value of tabulated data unless the original stress-strain curves are included. Thus, Figures 17, 18 and 19 are valuable in the sense that they show the results of

the tensile tests performed. One should readily note from these curves that for temperatures higher than 400°C the curves are spread much further apart than they are below this temperature. The predominance of the slippage deformation mechanism in this range for uranium may be the cause of that.

One can see directly from the stress-strain curves (Figures 20, 21 and 22), how the rate of loading influences the tensile properties of uranium. For the three different strain rates in Figures 20 and 21, the curve corresponding to the low rate of loading is predominantly on the lower side of the three and the other two respectively higher as their strain rates increase. However, all three curves in these two plots are quite close together. Figure 22 brings out the role that temperature plays since its values are taken at 550°C and Figures 20 and 21 are plots at 150°C and 350°C . So, the rate of loading influence on normal alpha uranium is greater at the higher temperatures than at room temperature. Of course, creep will play more of a major role as the temperature reaches higher limits also.

SUMMARY AND CONCLUSIONS

The investigation consisted of performing 40 tensile tests on normal alpha uranium in order to determine the influence of the rate of loading on the tensile properties of alpha uranium.

The tests were conducted in the temperature range from 25°C to 600°C at three constant loading rates (0.0017 min.⁻¹, 0.0130 min.⁻¹ and 0.0400 min.⁻¹).

The conclusions made from a study of the results are

1. The tensile properties of uranium are influenced by the rate of loading, however the effect of a rate change is much less, in magnitude, than the effect caused by a change in temperature.
2. The tensile strength, yield strength and modulus of elasticity are the properties of uranium most affected by the rate of loading, especially at the higher temperatures. A general statement can not be made about the influence of rate of loading on the percentage elongation (in 1.5 inch gage length) and the percentage reduction in area for uranium but the lowest strain rate seems to give the lowest values for both of these properties in the majority of cases.
3. The slope of the uranium stress-strain curve in the region of plastic flow is affected by the rate of loading and in general, the smallest slope is observed for the lowest

rate of loading.

4. The lowest rate of loading appears to cause the smallest amount of strain hardening in uranium at a specific temperature.
5. The predominance of the twinning and slip mechanisms of deformation in uranium may not only be affected by temperature but also by rate of loading.

SUGGESTED TOPICS FOR FURTHER INVESTIGATION

A more complete analysis to observe the effect of rate of loading on twinning and slip mechanisms in uranium might turn out to be very interesting. This same analysis might be carried out on other materials which display a change in the predominant mode of deformation from twinning to slip at a definite temperature. Thus, one might be able to generalize about such an effect.

A second field of inquiry might have to do with a consideration of the region of validity of the equation $\epsilon = A \sigma^m$ as seen in Figures 13, 14 and 15 of this thesis. One could look into the reason behind the variation with temperature in the limits of validity as well as changes in the size of the limiting region for temperature changes. Thermal expansion of uranium, which simply causes a separation of the atoms in the array, may have a great deal of significance in connection with this.

Since a change of strain rate was found to influence only slightly the slope of the stress-strain curve in the plastic region compared to the effect of temperature, equations for prediction of stresses in flexural creep might be able to utilize such a slope. This could prove to be an interesting source of analysis also.

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APPENDIX

Figure 23. Original stress-strain curve for highest rate of loading at 150°C

Figure 24. Original stress-strain curve for medium rate of loading at 350°C

Figure 25. Original stress-strain curve for lowest rate of loading at 600°C