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THE TENSILE PROPERTIES OF URANIUM IN
THE INELASTIC RANGE OF STRESS

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THE TENSILE PROPERTIES OF URANIUM IN THE INELASTIC RANGE OF STRESS*

Robert W. Lewis and Glenn Murphy

I. ABSTRACT

Tensile tests were made on specimens of uranium at strain rates varying from 0.0003 min^{-1} to 0.003 min^{-1} and at temperatures from 25°C to 300°C to study the effect of these variables on the strain hardening of the metal. At room temperatures an increase in yield strength of 100 per cent may be induced by a prior loading into the plastic range. Within the limits studied the effect of rate of strain upon strain hardening is negligible. Other factors being equal, the potential strain hardening decreases with an increase in temperature. The data are presented in tables and on graphs.

II. INTRODUCTION

One important characteristic of metals is their ability to strain harden. A direct method of studying strain hardening is to examine the simple relation between stress and strain as may be obtained from a tensile test. In this investigation uranium was subjected to tensile tests in which the parameters of temperature, strain rate and load cycling are varied in order to determine the influence of each on the strain hardening properties of the metal.

Strain hardening may be defined, for this investigation, as the increase in the strength of a metal that occurs after the metal has started to slip. This definition must be limited to strain taking place at a constant rate to avoid being applicable to a viscous fluid. Perhaps the best indication that strain hardening has occurred in a specimen is an increase in its yield strength. Changes in other properties may also be indicative. Various investigators have observed changes in the density, electrical conductivity, magnetic properties, resistance to wear and indentation hardness which accompany the phenomenon of strain hardening. The instantaneous rate of strain hardening is usually thought of as the slope of the stress strain curve of a constant strain rate test in the inelastic range of stress.

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The scope of the experimental program was limited by the available equipment and by the difficulty in testing uranium at high temperatures. The tests were conducted on a short time basis using an ordinary tensile testing machine. The range of test temperatures was from 25°C to 300°C while the strain rate was varied from 0.0003 in./in./min to 0.003 in./in./min. The magnitude of strain for each loading cycle was varied from 0.003 in./in./cycle to 0.009 in./in./cycle. One loading cycle consisted of loading to a given strain and unloading.

III. REVIEW OF LITERATURE

Theories that explain strain hardening in metal crystals, on the atomic level, are necessarily based on an atomic theory of slip. The accepted theory that explains slip in metal crystals is known as dislocation theory. Dislocation theory was introduced about 1934 by Taylor (1), Orowan (2) and others. The main features of the dislocation theory are as follows:

1. Perfect crystals are very strong.
2. Actual crystals are nearly perfect but contain imperfections. The critical shearing strength of the crystal is very sensitive to these imperfections.
3. Slip does not take place simultaneously but as a consecutive movement of dislocations through a crystal.
4. A dislocation may be thought of as a line imperfection forming the boundary within the crystal of a slipped area.
5. A line imperfection that lies normal to its slip vector is called an edge dislocation and one that lies parallel to its slip vector is called a screw dislocation.

The following theories of strain hardening may be grouped into three divisions; the exhaustion type theory, the dislocation impediment type theory and the dislocation interaction type theory.

The exhaustion type theory, described by Woolley (3), is based on the concept that all metals contain a finite number of regions of high internal stress. From each of these regions a dislocation may be liberated by the application of a sufficiently large external stress. These regions are called partial dislocations, and the stress necessary to convert them to mobile dislocations is called the activation stress. This theory assumes that hardening results from the exhaustion of the supply of available dislocations at a certain stress level.

A variation of this theory is described by Koehler (4) in which dislocations are not already present in a low energy state but are generated by a mechanism known as a Frank-Read mechanism (5). Koehler assumed that hardening resulted

because these mechanisms could generate only a limited number of dislocations at a certain energy level. He based this assumption on electron microscope data published by Brown, who found only a finite amount of glide per slip lamella in aluminum.

The dislocation impediment type theory explains hardening as the result of impediments to the movement of dislocations. In Taylor's original paper on dislocation theory he described a theory of hardening that is of this type. By computing the theoretical stress field that would surround a dislocation, he illustrated the manner in which dislocations would be obstructed in their movement by dislocations in parallel slip planes. From his analysis he concluded that a large number of faults or dislocations would harden a crystal instead of weakening it because the dislocations would interfere with the movement of each other. Taylor's theory is weakened by the fact that a theory of this type does not explain why the dislocations do not move back when the stress is reversed.

Mott's theory (6) of strain hardening falls into the impediment class also. His theory is very similar to Taylor's theory except he makes use of an obstacle called a sessile dislocation. Lomer (7) described a sessile dislocation as a dislocation that is formed by the combination of two dislocations intersecting each other on a given slip plane. The resulting dislocation is restricted to movement on planes that are not common slip planes. According to Mott, the forming of these sessile dislocations would block further movement of mobile dislocations and result in increased strength.

The third type of theory is the dislocation interaction type. The last section described how dislocations may be restricted in their movement by the conditions surrounding them such as the stress fields of other dislocations. Dislocations may also be restricted in their movement by changes that take place in the shape of the dislocation itself as a result of interaction with other dislocations. Simple geometry indicates in general that a dislocation that intersects another dislocation will lengthen and thus increase its energy content. Read, (8) page 82, illustrated this action as shown in figure 1.

Figure 1a

Figure 1b

The Intersection of Two Edge Dislocations

In figure 1a dislocation XY moving on its slip plane Pxy is about to cut the dislocation AD. In figure 1b dislocation XY has cut through AD. Now AD has a unit jog PP'.

A much more important mechanism of interaction hardening is that illustrated by Read, (8) page 84. Figure 2 shows that a jog produced by the intersection of two screw dislocations is restricted in its movement because it must climb, or move perpendicular to the slip vector, in order to move with the dislocation. Climbing requires a greater expenditure of energy because it requires mass transport of atoms.

Consider AB as a stationary screw dislocation. Due to this dislocation the crystal consists of a single atomic plane in the form of a helicoid, or spiral ramp. The illustration shows only the planes between the atoms. Line EF is a second screw dislocation moving from right to left on an intersecting plane. When EF reaches point A a portion of it jogs down to the next plane. Since a jog can glide only in the direction parallel to the moving dislocation, it must climb to move along with E'F'. The shaded portion of Figure 2 represents the jog. This feature of intersecting screw dislocations thus provides an important feature of the strain hardening.

Figure 2

The Intersection of Two Screw Dislocations

Hardening resulting from various combinations of different types of mechanisms cannot be excluded. Koehler (4) pointed out that hardening resulting from the combining of intersecting dislocations cannot occur in hexagonal crystals which have only one slip plane. Thus face-centered cubic and body-centered cubic crystals, which can harden not only from source hardening but also from interaction hardening, would be expected to harden at a faster rate. This conception agrees with the observation of Schmid and Boas, (9) page 125.

The preceding section has described briefly the main points of the various theories of work hardening. At the present time none of these theories have been developed to the point that they can be used quantitatively to describe or predict strain hardening without the adoption of a highly artificial model. The implication that the theories of strain hardening are still in the speculative stage is not intended. Actually, a great deal of evidence that dislocations do exist has been found by the use of the electron microscope (10), and a great many of the basic concepts essential to the theory of strain hardening have been worked out. Due to the varied and complex nature of the factors that affect strain hardening, a complete theory still lies beyond the realm of present day knowledge.

IV. REVIEW OF THEORETICAL EQUATIONS RELATING STRESS, STRAIN, STRAIN RATE AND TEMPERATURE

The influence of stress, strain, strain rate and temperature on the mechanical properties of metals has been the subject of numerous investigations. Many investigators have concerned themselves with finding the influence of only one of these parameters on some property of the metal. For instance, a great deal of work has been done on the problem of determining the influence of the strain rate on the yielding phenomenon of steel. Equations that relate stress, strain, strain rate and temperature as a single valued function are known as mechanical equations of state. The existence of a mechanical equation of state requires that the stress necessary to produce a certain strain at a given temperature depends only on the instantaneous values of temperature and strain rate. Although no simple single equation of state seems likely to exist, several equations of this type have been shown to apply to various metals over limited ranges.

A. Equivalent Strain Rate Parameter

In 1944 Zener and Holloman (11, 12) proposed a quantitative relation between the effects of temperature and strain rate. They suggested that the true stress σ (the instantaneous load divided by the instantaneous area) at a given strain ϵ could be expressed by the function

$$\sigma|_{\epsilon} = f(\dot{\epsilon} e^{Q/RT}) = f(P) \quad (1)$$

where $\dot{\epsilon}$ is the strain rate, T is the absolute temperature, R is the universal gas constant and Q is a constant of the material. In general the function $\sigma = f(\epsilon, \dot{\epsilon}, T)$ may be considered as a family of surfaces having ordinates of σ and horizontal co-ordinates of ϵ and $\dot{\epsilon}$. The symbol $\sigma|_{\epsilon}$ signifies the equation of the line formed by the intersection of a plane normal to the ϵ axis and the surface described by the function.

For low temperatures Q has been measured to be about 10,000 cal (gm mol)⁻¹, for several steels and since R is 1.987 cal deg⁻¹ mol⁻¹, the exponent becomes approximately 5000/ T . The parameter P then has the value

$$P = \dot{\epsilon} e^{5000/T} \quad (2)$$

for steel. The parameter P is seen to be a strain rate modified by the temperature.

B. Velocity Modified Temperature Parameter

MacGregor and Fisher (13) have proposed that instead of expressing the true stress as a function of three variables,

$$\sigma = f(T_R, \dot{\epsilon}, \epsilon) \quad (3)$$

Figure 3

Variation of the Function $\sigma = f(\epsilon, \dot{\epsilon}, T)$ at a given strain ϵ_0 .

T_R , the absolute temperature in degrees Rankine, and $\dot{\epsilon}$ could be combined in one parameter T_m . The parameter T_m would be a velocity modified temperature, and the true stress could be expressed as a function of two variables.

$$\sigma = f(T_m, \epsilon) \quad (4)$$

The expression for T_m was given as

$$T_m = T_R \left(1 - k \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \quad (5)$$

where K is a constant for the material selected, and $\dot{\epsilon}_0$ is an arbitrary reference strain rate. Equation 5 is derived from an earlier expression,

$$\dot{\epsilon} = \dot{\epsilon}_0 H e^{-Q/RT} \quad (6)$$

which is credited to Eyring (15) and Kauzman (16) and is based on an absolute reaction rate.

C. General Equation of Flow

Lubahn (14) has derived a general expression relating stress, strain, temperature and strain rate. His derivation was based on certain relations that have been observed in metals.

$$\sigma = A \epsilon^M \Big|_{\dot{\epsilon}, T_R} \quad (7)$$

$$\sigma = B \dot{\epsilon}^N \Big|_{\epsilon, T_R} \quad (8)$$

$$\frac{Q}{R} = T_R \left(\ln H - \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \Big|_{\sigma, \epsilon} \quad (9)$$

Equations 7 and 8 are empirical and equation 9 was derived from equation 6. From these relations a general equation was developed.

$$\sigma = C G^{T_R} \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right)^{D T_R} e^{(E - F T_R \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0})} \quad (10)$$

In this equation C, D, E, F, G and $\dot{\epsilon}_0$ are coefficients.

V. THE EXPERIMENTAL PROGRAM

The experimental program included thirty-six tensile tests. In each test the temperature was held constant, the strain rate was held constant, and the loading was done in cycles. The purpose of loading in cycles was to obtain data on the increase in the yield strength of the specimens.

Prior to these tests a series of tests was run to determine the maximum range of variables that could be obtained with the available equipment. It was found that if the loading value on the testing machine was placed at one setting, the rate of strain was not constant throughout the course of the test but often increased to two or three times its original value. To remedy this difficulty it was necessary to adjust the loading valve manually throughout the test. The rate of strain was noted by placing a pointer against the revolving drum of the stress strain recorder and marking time intervals on the recording paper. It was found, with practice, that a constant strain rate could be maintained with accuracy up to speeds of 0.003 in./in./min. Above this speed, however, the drum was revolving too fast for manual adjustment. The lower limit of the rate of strain was found to be approximately 0.0003 in./in./min due to the characteristics of the testing machine.

The temperature range was limited by the rapid oxidation of the test specimens at elevated temperatures. Silver plating was used to prevent oxygen from reaching the surface of the test specimens, but this plating broke down at temperatures above 300°C. Some preliminary time was spent in an effort to develop a coating that would withstand higher temperatures. Sandwich type coatings of silver on copper on silver and chromium on copper on silver were found to be slightly more effective than pure silver, but no coating was found that would prevent oxidation from taking place throughout six loading cycles at 400°C.

A. Description of the Test Specimens

The test specimens were approximately $2 \frac{3}{8}$ in. in overall length, with a 0.252-in. diameter test section which was $1 \frac{1}{2}$ in. long. Both ends were threaded with $\frac{3}{8}$ in. threads with 16 threads per in. The specimens were machined from slugs 8 in. long and 1.4 in. in diameter. Each slug was sawed into longitudinal quarters and the specimens were machined from these quarters. Each specimen that was tested at an elevated temperature was electroplated with silver to an average thickness of 0.003 in.

The uranium slugs were fabricated from rolled rod, beta treated with the chemical specifications shown in Table I.

Table I

Chemical Specifications of Uranium Slugs
Furnished by Fabricator

Impurities %	C >0.1	Cl >0.1	Cr >0.1	Si >0.1	B >0.1
Impurities %	Mg >0.1	Mn >0.1	Ni >0.1	N >0.1	

B. Description of Testing Equipment and Apparatus

The testing machine used was a 60,000-lb Baldwin-Southwark hydraulic universal testing machine with a Tate-Emery Load Indicator having three loading ranges. A Baldwin-Southwark microformer extensometer with a one-in. gage length was used in conjunction with a stress-strain recorder for room temperature tests. A Baldwin-Southwark furnace type extensometer also with a one-in. gage length was used at elevated temperatures. Both extensometers had a multiplication ratio of 1000 to 1. A 16-in. Marshall furnace was placed around the specimens at elevated temperatures, and a chromel-alumel thermocouple was fastened against the center of the test section for temperature control. The sweep-second hand of an I.B.M. wall clock was used to time the rate of strain.

C. Description of a Typical Test

The procedure of a typical elevated temperature test started with the placing of the test specimen into the fittings of the machine. A preliminary load of 250 lb. was put on the specimen after which the extensometer clamps were fastened loosely around it. By fastening the bottom of the clamps into the extensometer frame, the gage blocks were set at the desired gage length of one in. Next, the gage blocks were centered on the specimen and screwed down. The lower portion of the clamps were loosened at the extensometer and the load was removed.

After the extensometer had been secured to the specimen, a thermocouple was wired to the surface of the test section and the furnace was lowered. When the temperature of the specimen reached the desired level, the clamps were again fastened to the extensometer. If the strain recorder did not move it was taken as an indication that a state of thermal equilibrium in the specimen had been reached. The loading valve was then opened and several preliminary loadings were made in the elastic range to "set" the clamps on the specimen. The main portion of the test was then begun. The loading valve was set at the approximate setting required for the desired rate of strain and continually adjusted throughout the loading and unloading portion of the test. A complete test consisted of six loading cycles with a lapse of four minutes between cycles. After the sixth cycle was completed, the extensometer was disconnected and the loading valve was opened to a constant setting, which produced an approximate strain rate of 0.003 min^{-1} , until failure occurred.

D. Presentation of Data

The tensile properties of the specimens obtained from the test data are given in Table II. All calculations are based on the nominal diameter of the test specimens, 0.252 in., unless the measured diameter fell outside a range of ± 0.002 in. If the measured diameter fell outside this range the actual minimum initial diameter was used for calculations.

In some cases, especially at low temperatures, the stress-strain curve had little or no straight line portion on the first cycle. The second and following cycles, however, always exhibited a straight-line region. The modulus of elasticity reported in Table II is the average value of the first six cycles. The yield strengths listed in Table III were computed using the average modulus described above.

The reason for not testing some specimens to failure was twofold. It was desirable to know if the silver plating was holding up throughout the period of cycling, and the reduction in diameter that took place as a result of six cycles could be measured directly.

In Table III are listed the yield strengths for each cycle of every test. The yield strengths were computed using the average modulus of each test. The values that are missing in Table III were not obtainable due to the fact that the inelastic strain in these cycles was not of sufficient magnitude to extend to a 0.1 per cent offset.

Figure 4 illustrates the first six cycles of the test number eight, conducted at 25°C, drawn to a common origin. Figure 5 illustrates a similar plot of test number thirty-five which is the comparable test conducted at 300°C. Figure 6 shows the first cycle of four tests, each similar in every condition except temperature. The average yield strengths for the first cycles are shown plotted against temperature in figure 7. Each point in figure 7 is the average value of the yield strength computed from three tests conducted under similar conditions. The average yield strengths for the first cycles are plotted against strain rate in figure 8, and again each point is the average of three values as in the previous figure. The vertical lines in figure 8 indicate the maximum variation from the average at each point.

The rate of strain hardening, $\partial\sigma/\partial\epsilon$, is considered to be the slope of the stress strain diagram for a constant strain rate test. Figures 9, 10, 11 and 12 illustrate the slope of the stress strain diagram divided by the average modulus of elasticity E for each test plotted against the ratio σ/σ_u (σ_u is the ultimate strength). The parameters of the tests represented by figures 9, 10, 11 and 12 were the same except temperature which was varied. Test number twenty-eight was interrupted after the first three cycles due to difficulty with the extensometer. Cycles number four and five of test number twenty-eight were conducted after the specimen had cooled and been reheated.

Table II

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Tensile Properties of the Test Specimens

Test No.	Temp. (°C)	Strain per cycle (in./in.)	Strain rate (min ⁻¹)	Modulus of elasticity (PSI X 10 ⁶)	Yield strength at .1 per cent offset (KSI)	Ultimate strength (KSI)	Per cent decrease in area	Per cent elongation in 1 in.	Slug no.
1	25	.009	.0030	23.1	33.3	89.4	8.8	5	11
2	25	.009	.0016	21.7	35.0				11
3	25	.009	.0003	21.8	35.9	92.6	8.8	8	11
4	25	.006	.0030	20.1	31.9	90.3	8.8	10	11
5	25	.006	.0016	22.7	33.7	89.8	8.8	9	11
6	25	.006	.0003	21.7	33.0	93.5	8.0	8	11
7	25	.003	.0030	21.5	33.3				11
8	25	.003	.0016	22.1	33.2	93.0		8	11
9	25	.003	.0003	21.8	32.0	90.0	11.2	9	11
10	100	.009	.0030	20.3	32.4	84.2	15.6	19	13
11	100	.009	.0016	26.6	30.4	80.6	29.6	17	13
12	100	.009	.0003	17.6	31.5	74.2	32.2	18	14
13	100	.006	.0030	20.0	31.2	83.3	14.0		13
14	100	.006	.0016	17.7	29.0	84.5	13.6	15	13
15	100	.006	.0003	18.4	33.3				14
16	100	.003	.0030	16.9	29.0	85.2	23.4		13
17	100	.003	.0016	15.9	29.0	85.0	21.6	20	13
18	100	.003	.0003	20.5	28.2	77.1	22.0	13	14
19	200	.009	.0030	21.1	29.3	59.6	43.6	33	12
20	200	.009	.0016	18.5	28.5	60.8	30.8	28	12
21	200	.009	.0003	17.3	27.2	57.5	36.0	31	12
22	200	.006	.0030	18.5	25.6	53.9	42.2	15	11
23	200	.006	.0016	21.8	27.6	61.4	37.8	32	12

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Table II (Continued)

Test no.	Temp. (°C)	Strain per cycle (in./in.)	Strain rate (min ⁻¹)	Modulus of elasticity (PSI X 10 ⁶)	Yield strength at .1 per cent offset (KSI)	Ultimate Strength (KSI)	Per cent decrease in area	Per cent elongation in 1 in.	Slug no.
24	200	.006	.0003	15.9	28.5	58.8	38.6	25	12
25	200	.003	.0030	19.5	29.1	65.3	36.8	35	12
26	200	.003	.0016	19.7	27.8	58.0	42.8	28	12
27	200	.003	.0003	20.5	26.7	58.1	39.6	36	12
28	300	.009	.0030	20.7	24.5	37.9	37.8	6	12
29	300	.009	.0016	18.5	21.2	36.9	31.6	31	13
30	300	.009	.0003	19.8	23.1				13
31	300	.006	.0030	20.1	24.0	38.7	44.0		12
32	300	.006	.0016	21.8	23.0	39.9	37.0	37	13
33	300	.006	.0003	21.9	23.3				13
34	300	.003	.0030	24.6	21.5	42.6	46.7	23	12
35	300	.003	.0016	18.2	23.2	37.3	37.8	11	12
36	300	.003	.0003	21.4	26.2	41.2	40.8	25	13

Table III

Yield Strength at Each Cycle at .1 Per cent Offset

Test no.	Temp. (°C)	Yield strength in KSI cycle number						Per cent increase in 6 cycles
		1	2	3	4	5	6	
1	25	33.3	55.3	62.9	65.0	68.4	67.0	101.0
2	25	35.0	55.8	63.3	63.5	64.3	65.0	85.7
3	25	35.9	54.8	61.8	67.0	71.0	72.0	100.5
4	25	31.9	48.4	54.5	58.2	60.7	62.2	95.0
5	25	33.7	50.1	55.7	59.2	60.5	61.7	83.1
6	25	33.0	49.6	55.4	58.2	61.1	64.0	93.8
7	25	33.3	42.2	46.6	48.4	50.8	62.0	86.2
8	25	33.2	41.0	45.7	47.6	49.7		
9	25	32.0	40.0	43.7	45.9	48.0	49.1	53.4
10	100	32.4	48.1	52.7	53.7	53.0		
11	100	30.4	47.2	52.1	56.2	52.5	61.2	101.5
12	100	31.5	48.3	53.0	55.0	55.1	55.0	74.6
13	100	31.2	44.0	48.3	51.0	52.8	54.6	75.0
14	100	29.0	44.3	50.2	53.0	55.9	57.1	96.8
15	100	33.3	47.5	52.5	55.8	58.8	59.9	79.8
16	100	29.0	34.7	38.0				
17	100	29.0	36.0	38.7	40.7	42.7		
18	100	28.2	37.2	41.0	43.3	45.2	46.0	63.1

Table III (Continued)

Test no.	Temp. (°C)	Yield strength in KSI					Per cent increase in 6 cycles	
		cycle number						
		1	2	3	4	5	6	
19	200	29.3	45.4	49.2	51.6	52.5		
20	200	28.5	40.5	44.8	46.8	47.2	47.5	66.6
21	200	27.2	39.5	43.0	45.0	45.5	45.4	67.0
22	200	25.6	36.1	39.4	40.5	42.0	43.3	69.2
23	200	27.6	39.0	42.8	44.2	45.9	46.2	67.3
24	200	28.5	39.8	43.5	45.5	45.7	47.0	64.9
25	200	29.1	38.0	41.1	43.1	44.0		
26	200	27.8	33.7	36.3	37.2	38.6	39.6	42.4
27	200	26.7	33.0	34.3	36.8	36.7	38.5	44.2
28	300	24.5	30.5	32.3	27.5	34.6		
29	300	21.2	30.5	31.9	32.8	32.8		
30	300	23.1	33.3	34.9	35.0	35.0		
31	300	24.0	32.0	34.0	35.0	35.0	35.5	47.9
32	300	23.0	31.5	33.6	34.6	34.9	35.0	52.2
33	300	23.3	31.8	34.0	34.0	32.0	34.2	46.8
34	300	21.5	31.8	34.3	35.5	36.2	37.0	72.2
35	300	23.2	32.7	28.5	29.6	30.1	30.2	34.5
36	300	26.2	30.0	32.0	33.8	33.1	34.0	29.8

FIG. 4 STRESS-STRAIN CURVE FROM TEST NO.8

FIG. 5 STRESS-STRAIN CURVES FROM TEST NO. 35

FIG.6 - VARIATION OF STRESS - STRAIN CURVES WITH TEMPERATURE

FIG. 8 RELATION OF YIELD STRENGTH TO RATE OF STRAINING

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FIG. 9 MODIFIED RATE OF STRAIN HARDENING AS A FUNCTION OF STRESS FOR TEST NO.1

FIG.10 MODIFIED RATE OF STRAIN HARDENING AS A FUNCTION OF STRESS FOR
 TEST NO.10

FIG. II MODIFIED RATE OF STRAIN HARDENING AS A FUNCTION OF STRESS FOR TEST NO. 19

FIG.12 MODIFIED RATE OF STRAIN HARDENING AS A FUNCTION OF STRESS FOR TEST NO.28

VI. DISCUSSION OF RESULTS

The unbroken specimens from tests number 2, 7, 15, 30 and 33 were measured to determine if any appreciable decrease in diameter had occurred as a result of cycling or oxidation. In Table IV are listed the diameters of these specimens.

Table IV
Diameters of Unbroken Specimens After Cycling

Test no.	Temp. (°C)	Minimum diameter (in.)	Variation in diameter (in.)	Oxidation
2	25	.251	.001	None
7	25	.241	.002	None
15	100	.249	.000	None
30	300	.249	.002	Slight
33	300	.246	.003	Slight

Test number 33 may be considered critical as far as susceptibility to oxidation is concerned inasmuch as it was subjected to the highest temperature for the longest test. Since specimen number 33 was only reduced 5 per cent in cross-sectional area it may be concluded that for each test the cross-sectional area was virtually the same for each cycle.

For the majority of the tests the temperature fluctuation was held within a range of $\pm 2^{\circ}\text{C}$, and the remainder were held within a range of $\pm 5^{\circ}\text{C}$. The variation in rate of straining was small except at the slowest speed where some difficulty was experienced due to the fact that the valve was practically closed on the testing machine. It was observed, however, that this difficulty had little effect upon the stress values as they exhibited only minor fluctuations.

A. Comparison of Results with Theoretical Equations

Certain theories relating stress, strain, strain rate and temperature for tensile tests have been found applicable by various investigators. In this section these theories will be applied to the test data to determine if the proposed relations exist.

1. Equivalent strain rate parameter

The equivalent strain rate parameter described in section three proposes a relation between stress and strain rate modified by the temperature. This relation was shown as:

$$\sigma = f(\dot{\epsilon} e^{Q/RT}) = f(P)$$

where T is the absolute temperature expressed in degrees Kelvin, and R is $1.987 \text{ cal deg}^{-1} \text{ mol}^{-1}$ the universal gas constant. The term Q is proposed as a constant of the material and is adjusted, presumably by trial and error, to give the smoothest curve. Figure 13 shows the stress corresponding to a constant strain of 0.006 in./in. and 0.018 in./in. plotted against the parameter P based on $Q/R = 5,000$. The value of $Q/R = 5,000$ was found to be approximately applicable to most steels by Zener and Holloman.

2. Velocity modified temperature parameter

The velocity modified temperature was given by equation 5 as:

$$T_m = T_R \left(1 - K \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \bigg|_{\dot{\epsilon}}$$

where $\dot{\epsilon}_0$ is a reference strain rate, and was chosen arbitrarily to be $0.001 \text{ in./in./min}$ for this investigation. The K values were selected as 0.01 to fit the data to the smoothest curve. MacGregor and Fisher found the value of K for steel to be approximately 0.01 . Figure 14 shows a plot of σ against the parameter T_m for a constant strain of 0.006 in./in. and 0.018 in./in.

Figures 13 and 14 indicate general agreement with both theories. Neither theory attempts to predict the shape of the curve but simply implies that a relation exists. Since both theories are somewhat insensitive to changes in strain

FIG. 13 VARIATION OF STRESS WITH PARAMETER, P

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FIG.14 VARIATION OF STRESS WITH PARAMETER T_M

rate, and the range of strain rates in the data is comparatively small, it is difficult to determine whether or not the parameters show the correct influence of the strain rate.

3. General equation of flow

The general equation of flow is derived from equations 7, 8 and 9. Equation 8,

$$\sigma = B \dot{\epsilon}^N \Big|_{\epsilon, T_R}$$

relates the effect of strain rate $\dot{\epsilon}$ and stress σ at a constant strain and temperature. This equation indicates a linear relation between $\ln \sigma$ and $\ln \dot{\epsilon}$. Figure 15 shows a plot of stress σ against strain rate $\dot{\epsilon}$ on log scales, and indicates that the variations in strength with changes in strain rate can be predicted fairly well by equation 8.

Equation 7,

$$\sigma = A \epsilon^M \Big|_{\dot{\epsilon}, T_R}$$

describes the relation between stress σ and strain ϵ for a test conducted at a constant strain rate and temperature. This relation may be checked by plotting $\ln \sigma$ against $\ln \epsilon$. However, a more sensitive check may be made by plotting stress σ against $\frac{d\sigma}{d\epsilon} / \frac{\sigma}{\epsilon}$. If equation 7 is applicable, then $\frac{d\sigma}{d\epsilon} / \frac{\sigma}{\epsilon}$ will be a constant for all values of σ . Figure 16 shows a plot of $\frac{d\sigma}{d\epsilon} / \frac{\sigma}{\epsilon}$ against σ / σ_u

for three typical tests and indicates that equation 7 is not applicable to the data. Since equation 7 is not applicable to the data, no attempt was made to evaluate the constants in the general flow equation.

VII. SUMMARY AND CONCLUSIONS

An experimental study was made to determine the effects of rate of strain and temperature on the strain hardening properties of uranium.

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FIG.15 VARIATION OF STRESS WITH STRAIN RATE
AT A CONSTANT STRAIN

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FIG. 16 VARIATION OF σ/σ_{ULT} WITH STRESS

Tensile specimens, 0.252 in. in diameter, were tested at various constant strain rates from 0.0003 in./in./min to 0.003 in./in./min, and at temperatures ranging from 25°C (room temperature) to 300°C.

From the results of this study and within limits of the tests, the following conclusions may be summarized:

1. At room temperature the yield strength at 0.1 per cent offset may be increased as much as 100 per cent by cycling.
2. Increasing the temperature lessens the percentage increase in the yield strength for comparable strains.
3. The percentage increase in yield strength is comparatively insensitive to changes in the constant rate of straining.
4. In general, the rate of strain hardening will increase with successive cycles of loading for a given stress.
5. The yield strength for the first cycle decreases nearly linearly with an increase in the temperature of testing.

VIII. SUGGESTIONS FOR FURTHER INVESTIGATION

The authors feel that it would be very desirable to establish or disprove the proposed relations in section four. If it is possible to prove that the stress could be expressed as a function of two variables instead of three, then, perhaps, this relation could be used to predict the effects of very slow rates of strain. Test data from experiments conducted over a much wider range of strain rates would be required for this purpose.

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