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METALLURGY AND CERAMICS

TRUE STRESS-STRAIN PROPERTIES OF NATURAL URANIUM

By
M. T. McGowan
R. M. Treco

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Bridgeport Brass Company
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OF NATURAL URANIUM

M.T. McGOWAN
R.M. TRECO

November 30, 1956

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R.S. FRENCH, CHIEF
METALLURGICAL RESEARCH

A.E. SCHUETZ, SECTION HEAD
ATOMIC METALLURGY RESEARCH

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I. INTRODUCTION

The ordinary form of tension test serves the purpose of determining many of the mechanical properties for materials and is the basis for plotting a stress-strain diagram. The conventional type of diagram, so derived, provides the appropriate data for engineering design and stress analysis work. Additional knowledge, other than that of elastic properties, is desirable from a tension test for use in metal forming operations such as drawing, extrusion and rolling. Consequently the true stress-strain tension test has been adopted. Among its advantages are:

- 1) The true stress present during the test is defined rather than the fictitious stress based on the original area of cross-section.
- 2) True strain is determined where the change in gage length is referred to the length from which that change is produced, rather than to the original gage length.

The metal working industry is particularly concerned with the ability of metal to withstand permanent or plastic changes in shape and the corresponding resistance of the metal associated with these deformations. Successful working of a metal requires a knowledge of the capacity of the material to accept stress capable of producing plastic deformation. This capacity lies between the limits of a threshold stress at which plastic deformation begins and a necking stress comparable to that exhibited in tensile testing. In order to evaluate the stress-strain relationship in

this region, some form of experimental test procedure must be used to provide accurate measurement and computation of the variables. The standard tensile test produces necking after relatively small strains resulting in a complex system of tri-axial tensile stresses replacing the single principal stress along the specimen axis. However, by pre-straining the metal with combined stresses and then tensile testing, it is possible to relate stress with strains occurring during large deformations. The useful characteristic of the additivity of true strains is realized in this way. The tension test obtained can be used to establish the relationship between stresses and plastic strains for any system of combined loads.

II. EXPERIMENTAL PROCEDURE

1. MATERIAL

The material used was natural uranium which had been hot-rolled to a diameter of 0.810" in the alpha phase. This material had a poor surface, being rough and seamed, so that it was necessary to centerless-grind the rods to obtain a good starting surface for deformation by swage reductions.

2. ANNEALING

Centerless grinding of this metal produces severe work hardening which requires annealing for further working. Annealing was carried out in a closed steel tube at 630°F for one hour. The surface of the annealed bars displayed very thin, short (1/2") ridges similar to the

corner of a razor blade erupted in a longitudinal direction.

3. SWAGING

Pre-straining of the rods was accomplished by swaging in a series of reductions. Dependent upon die size and springback, attempts were made to carry out reductions at 10% intervals to 80% followed by 5% intervals and a final reduction of 96.9%. This final reduction achieved a true strain of 3.48 in/in. These strains from swaging were combined with those of a subsequent tensile test to form a continuous stress-strain curve.

Table I lists the data pertaining to the swaging operations including the rod size following grinding, die size, swaged diameter, reduction of area, number of passes to swaged diameter and the true strain resulting from swaging.

It was found that swaging was quite successful when pass reductions were fairly high. The maximum reduction attempted in one pass was 47%. Although the speed of swaging was limited to 5 ft./min., the rods heated up considerably with pass reductions over 30%. The surface quality of the swaged rods varied. In many cases, longitudinal seams and defects were apparent. The better sections of each swaged size were selected and cut into 12" lengths for tensile specimens. In order to test the material and obtain as precisely as possible the true swaging strain effects, it was necessary to produce a reduced section. An electro-polishing method was considered the best means of obtaining this reduced section with the least likelihood of introducing extraneous strains prior

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TABLE ISWAGING DATA

<u>ROD NO.</u>	<u>CENTERLESS GRIND TO SIZE (in.)</u>	<u>DIE SIZE (in.)</u>	<u>DIAMETER (in.)</u>	<u>R.A. %</u>	<u>NO. PASSES</u>	<u>TRUE STRAIN $\bar{\epsilon}$ (in/in.)</u>
U-9	.500	-	.500	0.0	0	0
U-1	.520	.500	.499	7.9	1	0.082
U-2	.545	.500	.498	16.5	1	0.180
U-3	.571	.500	.502	22.7	1	0.258
U-4	.600	.500	.498	31.1	1	0.373
U-5	.525	.389	.392	44.3	1	0.584
U-2267A	.600	.389	.389	58.0	2	0.867
U-7	.600	.312	.319	71.7	3	1.264
U-8-1	.600	.250	.261	81.0	4	1.665
U-8-2	.600	.218	.220	86.6	5	2.007
U-8-4	.600	.187	.165	92.4	6	2.582
U-8-4A	.600	.125	.125	95.7	7	3.138
U-8-4B	.600	.110	.105	96.9	8	3.480

to tensile testing.⁽¹⁾

4. ELECTROPOLISHING FOR TENSILE PREPARATION

The reduced sections of the tensile bars were prepared electrolytically in a bath consisting of 9 parts "Butyl Cellosolve", 9 parts formula 30 denatured alcohol and 2 parts perchloric acid. Each specimen, as shown in Fig. 1, was held in a copper chuck which in turn was held in the chuck of a variable speed stirrer. Contact with the chuck was made by a piece of spring temper bronze strip on the end of a glass rod. A circular stainless steel cathode with an hourglass-shaped inner profile was positioned around the middle of the rod.

The rods were rotated at 100 to 200 rpm. Current densities of 2 to 10 amperes per square inch and voltages of 10 to 24 volts were used. The time required to remove 10 mils from the middle of the bar ran from 20 to 30 minutes. It was necessary to use glass cooling coils in this bath in order to maintain the temperature at 20-25°C. The bath performed much better at this temperature and the fire hazard was minimized. This method was successful in that a reduced center section was produced. However, a slight shoulder effect developed at the solution level which necessitated a blending operation using fine emery paper.

5. TENSILE TEST PROCEDURE

Duplicate and triplicate tensile tests were planned for the hot rolled rod and for the rods swaged to the varied reductions. All tests were made with an Olsen 60,000-lb. capacity universal testing machine using wedge grips. Autographic traces of load vs. extension were obtained

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Fig. 1 - Apparatus for Electropolishing Uranium Rod for Tensile Specimens.

with a 2-inch gage length extensometer and recording equipment. The rate of straining was maintained between 0.025 and 0.050-inches/min. Initial tensile testing of the hot rolled rod and those with 7.9% and 16.5% reductions resulted in jaw fractures. This was a result of the notch effect from the jaw grips, the net area being smaller than that of the electro-polished reduced diameter. This trouble was eliminated in the remainder of the samples by altering the grips and employing fine file inserts for contact with the rod surfaces during testing. The reduced sections of jaw failure specimens were machined approximately .050" more for retesting which proved successful.

The actual tensile testing technique for the prepared specimens was as follows:

- a) A load-extension curve was obtained using the extensometer until the recorder chart is traversed. At this point the extensometer was removed. (A partial unloading and reloading cycle is made during this period to determine an hysteresis loop for modulus of elasticity values).
- b) The load on the specimen was increased until approximately 5% elongation occurs as measured by dividers and the load removed.
- c) The permanent strain occurring between the 2-inch gage marks was noted with dividers, the extensometer replaced and a second load-extension curve was made.

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- d) Repetitions were made until the maximum load for the specimen occurred. At this point, the total elongation for the test was also measured with dividers.

Conversion of the recorded load-extension curves to true stress-strain data requires a knowledge of the instantaneous strains and areas for the applied loads. These are obtained from elongation values as recorded during testing. True strain can be related to the conventional strain and the instantaneous areas can be determined from the Poisson ratio effect as follows:

$$A_i = A_0 (1 - 2 U e_e) \quad \text{Eq. 1}$$

$$\bar{e} = \ln (1 + e_e) \quad \text{Eq. 2}$$

where A_i and A_0 are the instantaneous and original areas respectively.

U = Poisson's ratio for the metal

e_e = elongation strain

$\bar{e}$ = True Strain

A Poisson's ratio value of 0.19 was used for uranium for small strains and a theoretical value of 0.50 for larger plastic strains.

A typical load extension curve is shown in Fig. 2 for the hot rolled material and the conventional stress-strain relationship is drawn in Fig. 3. The latter figure illustrates the effects of pre-straining during tensile testing. As can be noted, each curve exhibits an elastic portion sloping upwards to the general contour of a continuous curve so that a combined stress-strain curve can be drawn.

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URANIUM U-9-#3

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FIG. 3

CONVENTIONAL STRESS-STRAIN

HOT ROLLED-U

P. MAX $\rightarrow$

III. EXPERIMENTAL RESULTS

The results of the tensile tests of the uranium are summarized in Table II. The conventional stress-strain properties are listed including the 0.2% yield strength, ultimate tensile strength, Young's modulus, % reduction in area and % elongation.

It appears that there is an orientation effect which is exerting an influence on the properties. The strength properties increase with cold work as is normally found. However, the reduction of area appears to increase to a peak at 71.7% reduction followed by a gradual decrease. At the maximum swage reduction of 96.9%, the reduction of area is still greater than that for the unworked material. The per cent elongation varies in the range of 11 to 19 to the 71.7% reduction, except for a low value of 8 at 22.7% reduction, followed by a gradual decline. The modulus increases and decreases during the lower swage reductions; however, it increases steadily at reductions of 58% and up.

Some of the discrepancies which appear in the results may be due to tensile test errors. These would occur from faulty measurements of load and dimension. The presence of hydrogen would also account for some of the inconsistencies in the results.

Figs. 4-7 show the original and worked structures of the material tested. The change in the structure with different degrees of swaging is evident.

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TABLE II

TENSILE TEST DATA

SPECIMEN NO.	% R.A. SWAGING	TRUE STRAIN $\bar{\epsilon}$ SWAGING	0.2% YIELD STRENGTH (p.s.i.)	ULTIMATE TENSILE STRENGTH (p.s.i.)	YOUNG'S MODULUS	REDUCTION AREA %	ELONGATION IN 2" %
U-9-1	As	0	68,900	140,550	11.3×10^6	14.0	11.0
2	Received		65,250	122,550	10.8×10^6	11.5	15.0
3	"		46,850	119,100	7.6×10^6	20.3	20.0
U-1-1	7.9	0.082	76,750	139,650	14.3×10^6	11.5	10.0
2			62,300	115,200	14.9×10^6	13.9	18.0
U-2-1	16.5	0.180	99,250	144,850	17.2×10^6	18.4	20.0
2			100,000	148,100	17.1×10^6	16.7	18.0
U-3-1	22.7	0.258	81,500	145,000	9.3×10^6	6.3	6.0
2			113,700	146,300	13.7×10^6	14.4	10.0
3			98,050	143,250	9.6×10^6	14.1	9.5
U-4-1	31.1	0.373	86,700	125,550	11.2×10^6	11.5	12.0
2			80,700	125,450	11.4×10^6	10.1	11.0
U-5-1	44.3	0.584	90,650	151,650	10.0×10^6	12.0	12.0
2			97,500	144,150	9.8×10^6	24.6	16.0
U-2267A1	58.0	0.867	99,150	152,950	9.9×10^6	19.8	11.0
2			101,700	146,900	9.7×10^6	30.0	17.0
3			83,350	158,700	10.3×10^6	21.6	11.0
U-7-1	71.7	1.264	108,900	166,300	10.1×10^6	36.8	10.0
2			94,300	158,150	10.4×10^6	36.0	12.0
3			95,150	162,000	10.3×10^6	-	-
U-8-1-1	81.0	1.665	94,250	183,700	10.4×10^6	29.7	7.0
2			99,000	183,900	10.8×10^6	35.9	9.0
U-8-2-1	86.6	2.007	134,550	192,950	11.0×10^6	29.6	5.0
2			131,100	197,900	10.7×10^6	29.6	6.0
3			117,650	196,200	10.8×10^6	20.4	5.0

TABLE II

- Continued -

SPECIMEN NO.	% R.A. SWAGING	TRUE STRAIN $\bar{\epsilon}$ SWAGING	0.2% YIELD STRENGTH (p.s.i.)	ULTIMATE TENSILE STRENGTH (p.s.i.)	YOUNG'S MODULUS	REDUCTION AREA %	ELONGATION IN 2" %
U-8-4-1	92.4	2.582	89,150	168,250	13.4×10^6	20.6	6.0
2			147,000	170,500	17.0×10^6	20.8	5.0
3			145,500	174,650	17.0×10^6	16.9	5.0
U-8-4A-1	95.7	3.138	135,300	180,750	18.3×10^6	-	-
2			151,950	184,300	19.1×10^6	-	-
3			132,500	186,000	19.5×10^6	20.0	3.0
U-8-4B-1	96.9	3.480	135,400	201,700	19.2×10^6	15.0	7.0
2			132,200	195,900	19.5×10^6	-	-
3			126,100	203,000	21.1×10^6	17.1	3.0

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Fig. 4 - Initial Hot Rolled Rod Structure. Average Alpha G.S. 0.022 mm.

Mag. 100X

Pd. Lt., E.P.

Fig. 5 - Same as above except Cold-worked by Swaging to 7.9% R.A.

Mag. 100X

Pd. Lt., E.P.

Fig. 6 - Alpha Hot Rolled Rod Cold-worked by Swaging to 58% R.A.

Mag. 100X

Pd. Lt., E.P.

Fig. 7 - Alpha Hot Rolled Rod Cold-worked by Swaging to 96.9% R.A.

Mag. 100X

Pd. Lt., E.P.

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IV. DISCUSSION

Following calculations of true stress and true strain for the material, the composite curve was obtained as shown in Fig. 8. The initial elastic portion is virtually perpendicular with this scale. Strain hardening occurs at a rapid rate up to approximately .06 strain. Beyond this point, the slope decreases rapidly and eventually levels off. The strength decidedly drops off at a strain of 2.04 and then increases again.

There are generally two anomalies in a curve of this type as noted above. In the transition region between the elastic and plastic portions there are a number of the experimental points which lie above the stress-strain curve. These points represent the effects of redundant work or extra strain energy due usually to frictional effects from the tools. The true deformation energy is that energy required to produce the desired change in shape as shown in (a) and (b) of Fig. 9. Extra frictional work is encountered at the surface of the rod, however, as shown in (c) of the same figure. This extra work becomes a negligible fraction of the total deformation work with reductions greater than about 20%. Consequently, the points at higher strains do not deviate from the curve appreciably. If it is desired to correct for redundant work, the tensile curve must be replaced slightly towards higher strains to compensate for the larger deformation work.

The second anomaly occurs at large plastic strains where there is

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FIG. 9 SOURCE OF REDUNDANT WORK

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a decided drop in the stress level. With increasing strain, the stress level again rises finally approaching the stress-strain curve extrapolated from lower values. While this effect might at first appear to be associated with errors in technique, closer examination shows this to be a true effect. The effect is not due to testing errors, being well outside the limits of accuracy of the testing methods. A possible source could be overheating during plastic working if recrystallization occurred. Metallographic examination shows that recrystallization did not occur, however. The same phenomenon has been observed in copper by other investigators as noted in a previous report.⁽²⁾ Although this drop-off of stress has been noted at large strains, it has not been satisfactorily explained to date. A possible explanation for this effect at large strains is that a complete re-orientation of the crystal structure occurs. Such a change in orientation may be the result of exhausting the operative slip planes for the major texture developed by the deformation process. With larger strains a new mode of deformation is required such that a new system of slip planes becomes operative. The decrease in stress level occurs at this critical strain when a major re-orientation occurs. The decrease in stress level can be attributed to the presence of new slip directions in which strain hardening has not yet begun. The steady increase in strength or hardness then develops as the new slip planes participate in the deformation process, eventually leading to the same stress values previously obtained. After the higher stresses have been reached, normal strain hardening continues

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and the stress-strain curve rises. This explanation, in brief, shows that a true change of regime occurs in the plastic stress-strain curve of metals at large strains, and suggests that the curve should actually be drawn through the experimental points. This is shown by the dashed portion of Fig. 8 for comparison with the usual extrapolated form of the curve.

In order to use the combined true stress-strain curve for plasticity calculations, it is convenient to convert the tensile data to true shear stress-strain values. This is conveniently done by means of the octahedral parameters, $\bar{\tau}_0$ and $\bar{\gamma}_0$, as defined by A. Nadai. The relations between the true tensile parameters and the true shear parameters are as follows:

$$\bar{\tau}_0 = \sqrt{2/3} \bar{\sigma}_1 = 0.471 \bar{\sigma}_1 \quad \text{Eq. 3}$$

$$\bar{\gamma}_0 = \sqrt{2} \bar{e} = 1.414 \bar{e} \quad \text{Eq. 4}$$

where $\bar{\tau}_0$ = true shear stress

$\bar{\sigma}_1$ = true stress

$\bar{\gamma}_0$ = true shear strain

$\bar{e}$ = true strain

In this way, a derived "universal" stress-strain curve is developed as shown in Fig. 10.

In practice, the universal stress-strain curve is used to compute the resistance of the uranium to deformation from combined strains. By calculating the principal true strains for a proposed mechanical deformation, the octahedral shear strain, $\bar{\gamma}_0$, may be obtained. The experimental

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$\bar{\tau}_0 - \bar{\gamma}_0$ curve is then used to obtain the corresponding shear stress from which a tool force may be derived.

It must be recognized that a single line curve is not quite "universal" in that metallurgical variations in the uranium or other metal produce a band of finite width due to such factors as grain size, preferred orientation or excessive non-metallic inclusions. Usually, it is not necessary to achieve high precision in plasticity calculations for fabrication tooling, so that the additional effort required to completely define the band width is rarely justified.

V. CONCLUSIONS

The preceding work has shown that a composite true stress-strain curve for uranium may be derived from a combination of swaging prestrains and conventional tensile testing. It is important to observe that considerable care must be taken to minimize experimental error and extraneous effects.

Stress-strain curves of this type often show a discontinuous drop in stress with large plastic strains. This change of regime which occurred with uranium has been previously observed in copper and steel by other investigators. An explanation of the change in regime based on crystallographic orientation has been proposed which explains the observed phenomena. Further work involving x-ray diffraction studies of the preferred orientation in the region of the discontinuity would be desirable.

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A number of experimental techniques, including electropolishing of tensile samples, have been successfully established.

VI. ACKNOWLEDGEMENT

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VII. BIBLIOGRAPHY

- 1) "Fabrication of Uranium Wire", Part III, AERE-M/R-1070, Haines and Mott.
 - 2) "A Characteristic Plasticity Function for some Copper Base Alloys", R.M. Treco and A.R. Pels, Bridgeport Brass Company, Issued May 1956.
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