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FLOW BEHAVIOR OF MULBERRY URANIUM

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Abstract

The mechanical properties of mulberry uranium were studied at strain rates from 10^{-4} to 5×10^3 $\sec^{-1}$ and at temperatures from 78°-770°K. The nonlinear loading and off-loading characteristics of this alloy received particular attention. This nonlinear behavior is the result of a γ_s to γ_0 phase transformation and a reversible, diffusion-controlled ordering effect.

Introduction

Recently considerable effort has been directed toward development of uranium alloys. Pure uranium is a poor engineering or structural material because of its relatively low strength, poor corrosion resistance, dimensional instability and the inability of conventional heat treatments to enhance its mechanical properties. The first alloys investigated were binary systems with a high degree of solubility in the γ region such as uranium-molybdenum, uranium-niobium and uranium-zirconium. However, each of these binary systems has some bad engineering properties. For example, the uranium-molybdenum alloys are susceptible to stress-corrosion cracking,[1] uranium-niobium alloys are weak,[2] uranium-zirconium systems are brittle.[2]

Attention was next directed to ternary systems which might combine the good properties of two binary systems. Mulberry uranium (7.5 wt% Nb, 2.5 wt% Zr, bal. U) is one of the most widely used alloys resulting from this investigation. This alloy has good strength, ductility, corrosion resistance and stability. It can be hardened by aging. Variation in aging time and temperature can vary its ultimate strength from 110 to 270 ksi. However, at the higher strengths the alloy becomes very brittle.

The most widely used heat treatment consists of a soak at 800° to 950°C for 1 hr per in. cross section, water quenched, followed by aging for 1 hr at 150°C. The time-temperature transformation curve[3] for mulberry appears in Fig. 1. One can see that the alloy has a γ_s phase following the γ quench. This 150°C aging process transforms some of the material to the γ_0 phase. Other aging processes may produce more or less of the γ_0 phase and may also produce some α'' phase. γ_s is a cubic structure having body-centered atoms slightly shifted. γ_0 is a tetragonal structure and α'' is a monoclinic structure.

The object of this series of tests is to investigate:

- the effect of strain rate on the flow stress,
- the abnormal behavior of mulberry at low strains, and

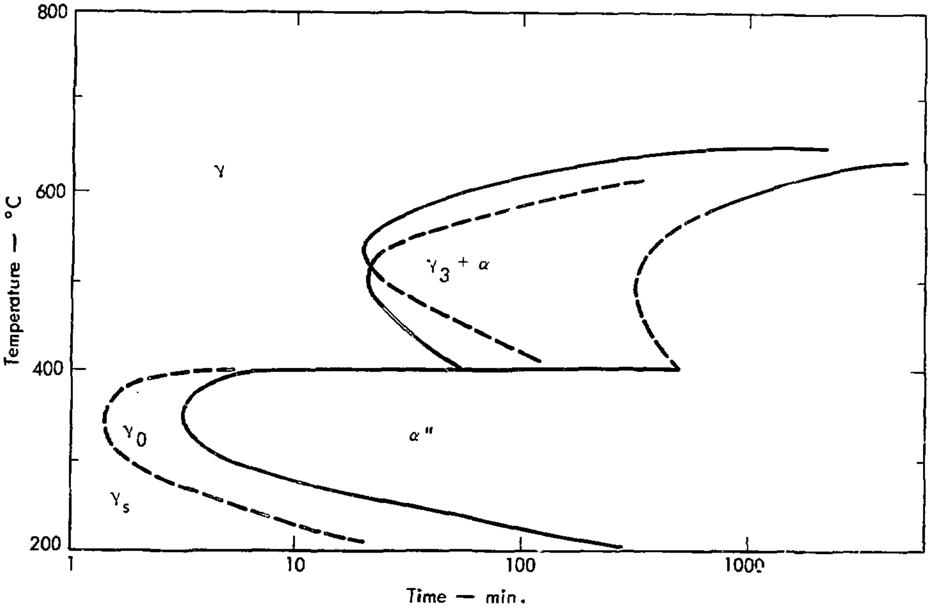

Fig. 1. Time-temperature transformation diagram determined by metallography and hardness.[3]

- the non-linear stress-strain relation during off-loading.

Several investigators have observed the abnormal behavior of mulberry at low strains. For example, Albright reports a linear stress-strain region up to 40 ksi and a second linear region above this stress.[4] He concludes that the difference in modulus values for these two regions is due to deformation resulting from a stress-induced phase transformation from γ_s to γ_υ. It appears that this phase transformation is only partly responsible for the double modulus behavior of mulberry. Other possible causes will be discussed in this paper.

Experimental

Tests were conducted in tension and compression on an MTS* universal test machine at strain rates from 10^{-4} to $10\ \text{sec}^{-1}$. For tests below $10^{-2}\ \text{sec}^{-1}$ a 1 in.-10% or a 1 in.-50% Instron extensometer was used to sense specimen deformation and data was recorded on an X-Y-Y' recorder. For the higher rate tests an Optron optical extensometer was

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*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

used to measure strain. Data was recorded as load and deformation versus time on one oscilloscope and as load versus deformation on another. Tensile tests at strain rates from 10 to 150 sec^{-1} were conducted on the modified Dynapak machine. Data was recorded as in the high rate MTS tests. Both tensile and compression tests were conducted at strain rates from 500 to 5000 sec^{-1} using the Hopkinson split-bar test technique.

Tests were also run at both low and elevated temperatures on the MTS machine. For elevated temperature tests specimens were heated with an induction coil. Power was supplied by a 450-kHz, 2.5-kW Lepel heating unit. This heating method brought specimens to the required temperature in about 10 sec. Specimens were allowed to soak at temperature for about 20 sec before testing. We believe no phase changes could have occurred in this short time period. Preliminary tests with this technique indicated that both radial and axial temperature gradients were less than 3%. Low temperature tests used a Missimers temperature chamber for first stage temperature drop to -50°C. A second stage drop was obtained by spraying liquid nitrogen into a second chamber surrounding the specimen.

A test series was also conducted to determine the acoustic emission during tensile loading. A specially designed, 10-ton capacity, hydraulically driven universal test machine was used for these tests. To reduce hydraulic noise from the test machine the servo-valve was removed and connected to the actuator by a hose. A PZT-5 piezoelectric crystal was coupled to the specimen with Dow Corning V-9 resin. The crystal output went through a preamplifier (0.1 to 0.3 MHz), totalizer and audio monitor. Data was recorded on X-Y plotters as summation of emission, rate of emission and rms value of emission versus strain in the specimen.

Compression specimens were cylindrical, 0.45 in. diam and 0.3-0.6 in. long. Tensile specimens for the universal test machine and Dynapak tests had a gage section 1.25 in. long by 0.25 in. diam. Hopkinson bar tension specimens had a gage section 0.25-0.5 in. long by 0.16 in. diam. Different specimens received three types of heat treatment as follows:

type A - soaked at 850°C for 1 hr in vacuum, water quenched.

type B - soaked at 850°C for 1 hr in vacuum, water quenched, followed by aging for 1 hr at 150°C.

type C - soaked at 850°C for 1 hr in vacuum, water quenched, followed by aging for 6 min. at 350°C.

Results and Discussion

EFFECT OF STRAIN RATE ON FLOW STRESS

A series of dynamic tests was conducted on type B alloy in tension at strain rates from 10^{-4} to 5×10^{3} sec^{-1} at temperatures from 22°C to 500°C. Results are shown in Fig. 2. The theoretical curve was obtained from the Peierls

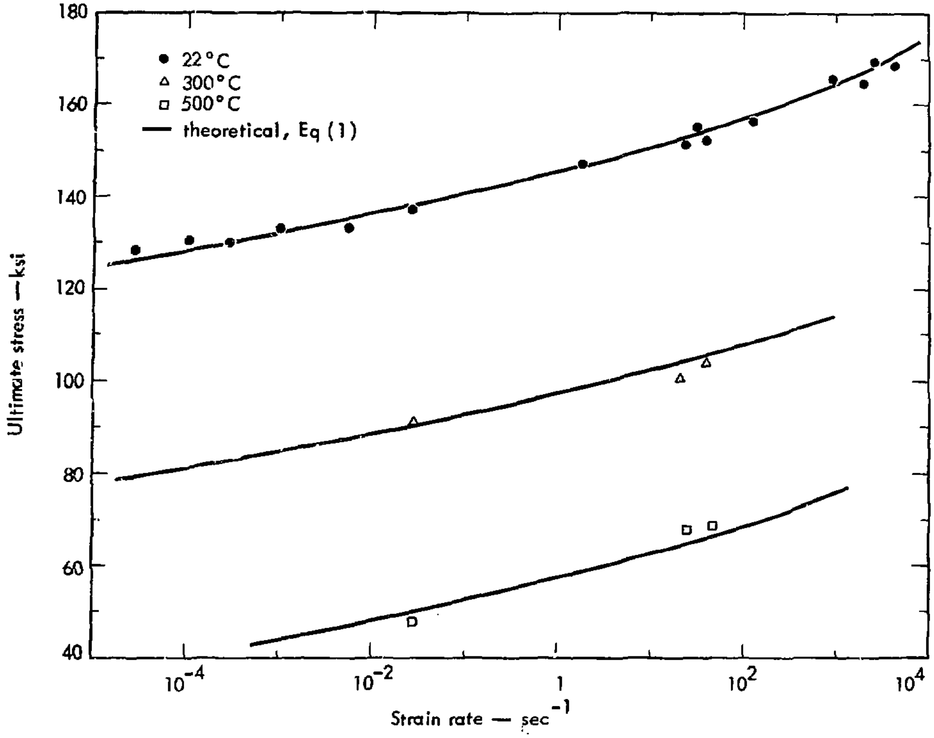

Fig. 2. Ultimate strength vs strain rate for type B mulberry.

model with dislocation dampening. The governing equation is

$$\dot{\varepsilon} = \frac{\rho b^2}{\frac{2w^2}{La\nu} \exp\left[\frac{2U_k}{kT}\left(1 - \frac{\sigma^*}{\sigma_p}\right)^2\right] + D/\sigma^*} . \quad (1)$$

The derivation and terms of this equation are explained in Ref. 5.

The ultimate stress (flow stress at about 5% strain) vs temperature needed to obtain some of the constants for Eq. (1) are shown in Fig. 3. It should be pointed out that although this model correlates well with data, we are not sure the Peierls process is the controlling mechanism for mulberry. Also, the presence of phase changes makes the theoretical analysis questionable.

An interesting feature of tests on type B and C materials at tensile rates higher than 10^3 sec^{-1} was the appearance of a large upper-lower yield stress. Furthermore, this yield drop appears more like an instability than a normal upper-lower yield phenomenon. This conclusion is supported by the absence of yield drop at low temperatures or in any test below 200 sec^{-1}. The cause for this behavior could be the γ_s to γ_0 phase

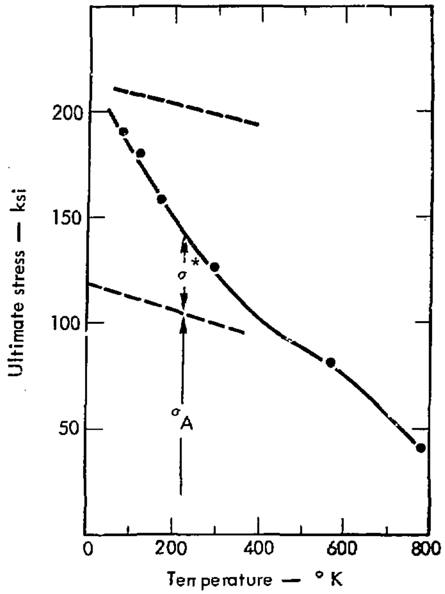

Fig. 3. Ultimate strength vs temperature for type B mulberry at a strain rate of 10^{-4} $\sec^{-1}$.

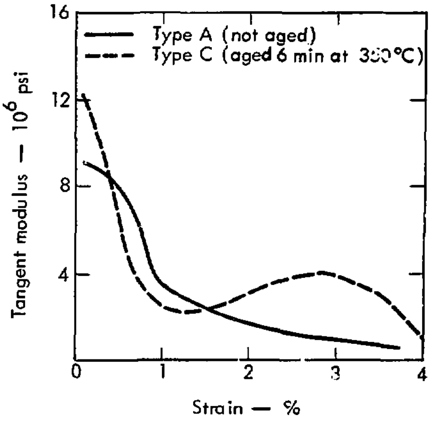

Fig. 4. Effect of strain on tangent modulus. Data taken at a tensile strain rate of 10^{-4} $\sec^{-1}$.

transformation or a diffusion controlled ordering process.

LOW STRAIN BEHAVIOR

The stress-strain relationship for mulberry appears to be nonlinear even at very low strain levels. Figure 4 shows changes in modulus for specimens subjected to heat treatments A and C as a function of tensile strain. The zero strain modulus was obtained from ultrasonic velocity measurements.[6] Figure 5 shows ultrasonic modulus values obtained at various temperatures. Figure 6 shows the effect of strain rate on low strain tensile behavior of type C alloy. It is evident that changes in rate effect the low strain behavior. The stress-strain behavior of type A (unaged) alloy was also nonlinear but quite different from the type C behavior. Figure 7 shows typical low strain behavior for a type A alloy in tension. Several low strain compression tests were conducted on types A and C materials. Results were similar to those obtained in tension.

Ordinarily the elastic (Young's) modulus is independent of strain rate. Thus, it appears that at low strains there is a time-dependent, nonlinear process operative. This process may be diffusion-controlled ordering, a phase transformation, actual plastic flow resulting from dislocation motion, or a combination of these processes.

NON-LINEAR OFF-LOADING PHENOMENON

The off-loading behavior of types A, B, and C mulberry shows similar nonlinearities for all three types of heat

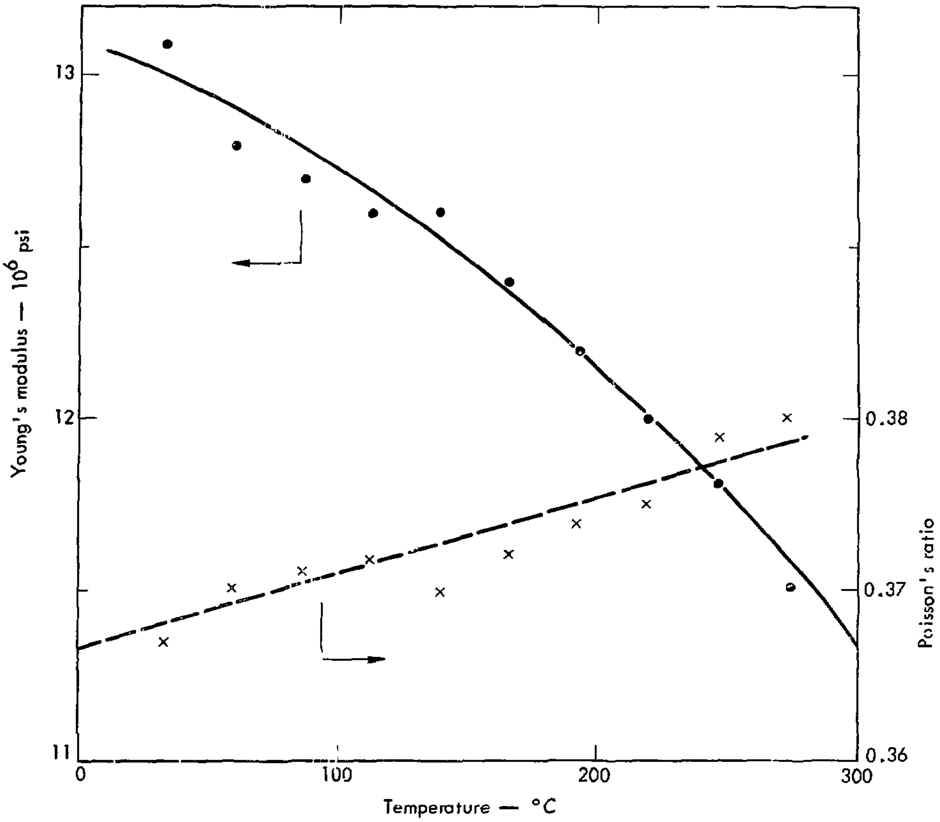

Fig. 5. Young's modulus and Poisson's ratio of type B mulberry. Data obtained by ultrasonic velocity measurements.[6].

treatment. When a specimen is loaded to some strain level and then cycled between this stress and zero stress a hysteresis loop results. Figure 8 shows results for a typical series of cyclic tests. It can be seen that during the first couple of cycles the amount of hysteresis decreases slightly and then remains constant during subsequent cycling.

When a specimen is off-loaded several times, each time at a different strain value, the off-loading curves were similar over ranges of equal stresses. For example, if a specimen is off-loaded from a strain of 1% (stress equals 60 ksi at 1% strain) then reloaded to a strain of 10% (where stress equals 140 ksi) and again off-loaded, the behavior is similar between stresses of zero and 60 ksi. Compression tests showed similar results.

These results indicate the off-loading nonlinearity is due to a repeatable,

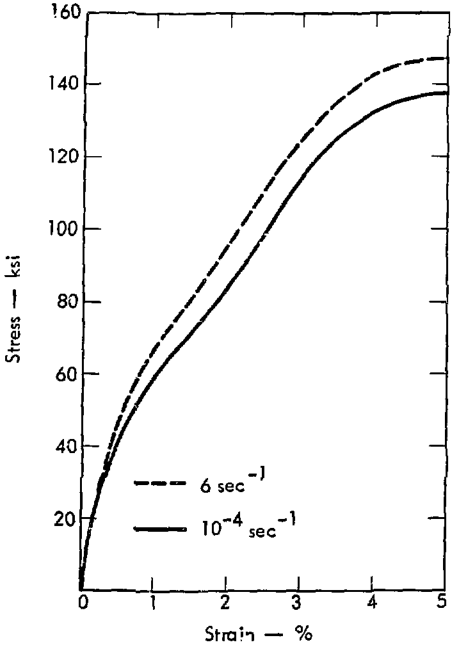

Fig. 6. Effect of strain rate on the tensile loading curve of type C alloy.

reversible process which is dependent upon the stress level. Since the stress dependence is repeatable we conclude that it may be connected with the elastic response of the crystal structure. Thus, we feel this behavior is caused by a diffusion-controlled ordering effect. Other possible causes are reversible phase transformations and reversible twinning.[7]

ACOUSTIC EMISSION-PHASE TRANSFORMATION TESTS

Tensile tests on type C alloy were conducted with acoustic emission techniques used to detect the phase transformation. Figure 9 shows a typical stress-strain curve with rms values of acoustic emission plotted versus strain. The usual high acoustic emission level seen only at very low strains is probably caused by dislocations being formed or breaking loose from pins. At about 1% strain acoustic emission again picks up and reaches a maximum at strains of about 4%. The emissions fall to approximately zero at 9% strain.

The emissions from 1 to 9% strain appear to be caused by the γ_s to γ_0 phase transformation. Several spot checks on the transformation were made by X-ray diffraction. Only a little γ_0 appeared after the 6 min age treatment; much more γ_0 (although not a complete transformation) appeared after loading to 5% strain. Thus X-ray diffraction results appear to

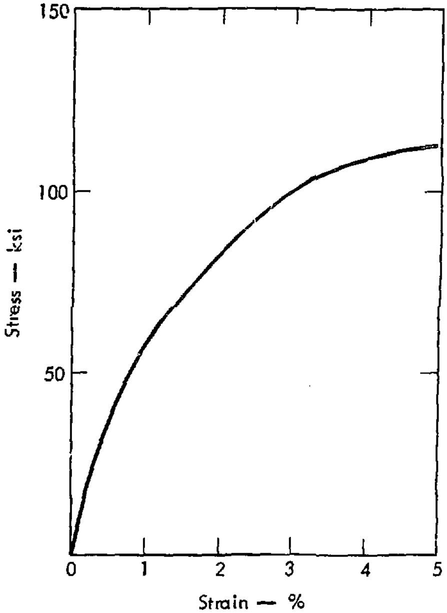

Fig. 7. Typical tensile stress-strain curve for type A mulberry at a strain rate of 10^{-4} sec^{-1}.

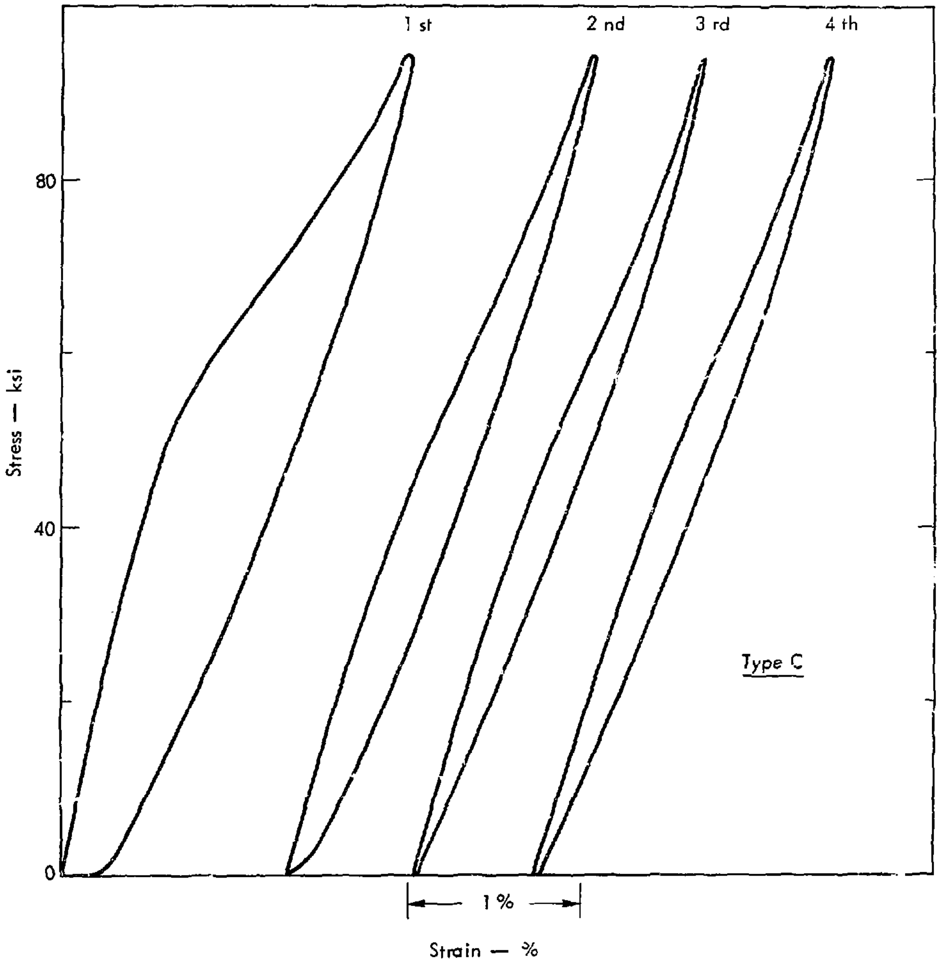

Fig. 8. Behavior of type C mulberry loaded to 2% tensile strain and then cycled to this stress level three more times.

substantiate acoustic emission findings. We also noticed that acoustic emissions disappeared upon off-loading.

Several tests were also conducted on mulberry which had been heat treated to form a stabilized α structure. Prior to yield large emissions were recorded. This is similar to type C alloy emissions. However, for strains beyond yield emissions were negligible for the stabilized structure. This result also tends to confirm that emissions from type C alloy were from the phase transformation.

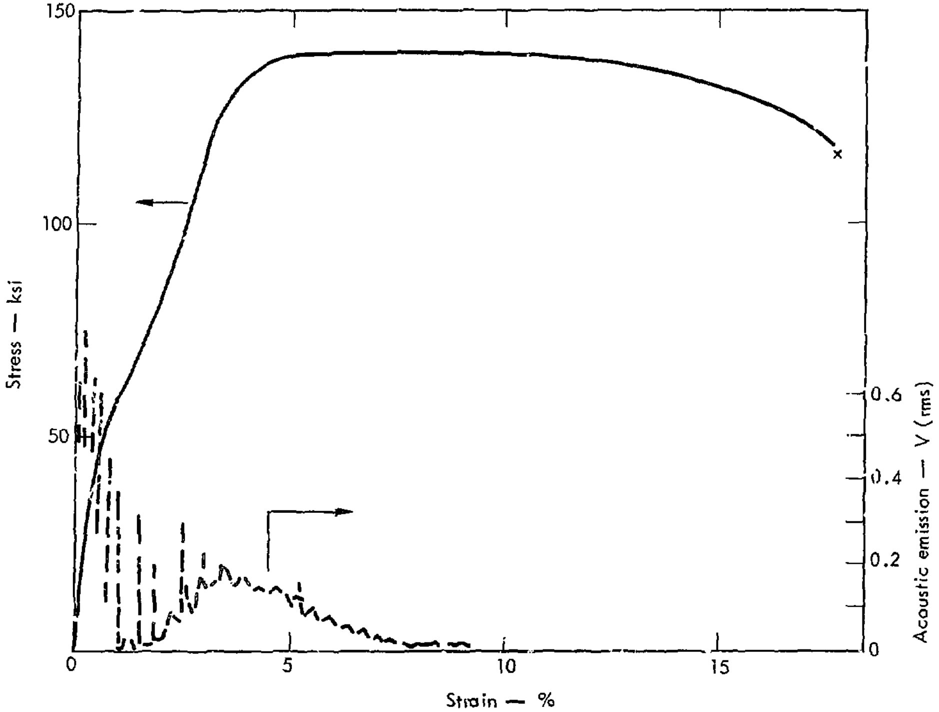

Fig. 9. Typical acoustic emission of a type C specimen during tensile loading at a strain rate of 10^{-4} sec^{-1} (gain = 96 dB). Specimen area reduction at fracture is 40%.

Conclusions

Originally this study was to be a complete investigation on the mechanical behavior of mulberry. This project has been cut short, however, by personnel reassignments. Thus the conclusions drawn are based on the trends of an abbreviated test series.

Deciding which mechanisms control the flow behavior of mulberry uranium involves analyzing the results of all the types of tests conducted. Based on these experiments we conclude:

- A γ_s to γ_0 phase transformation occurs from strains of about 1 to 9%. This transformation appears to be irreversible since acoustic emission became negligible upon off-loading, and subsequent cycles.
  This phase transformation causes some of the nonlinearity observed during loading at low strain values.
- At low strain levels a diffusion-controlled ordering process occurs. This process depends upon the

lattice structure and therefore is dependent upon stress. It also effects the low strain behavior and thus causes nonlinear loading and off-loading behavior.

- The nonlinear stress-strain behavior upon initial loading is caused by a combination of the phase transformation and ordering processes. Some plastic flow due to dislocation movement may occur during loading at low strain levels. However, such movement must be a minor contributor to low strain nonlinear behavior since cycling should eliminate this type of flow.
- The nonlinear off-loading is caused by the ordering process. We eliminate reversible twinning and reversible phase transformations because no acoustic emission was heard during off-loading.
- The large yield drop seen during dynamic tensile tests is caused by the ordering process. This process is rate dependent; if a test happens fast enough atoms have no chance to diffuse to their preferred positions during the time it takes the stress to reach yield. This temporary lattice structure distortion produces an increase in strength.

Recommendations

It is recommended that the following tests be conducted to validate the conclusions drawn from this test series:

- The uranium-niobium-zirconium ternary system produces many alloys with good mechanical properties. In view of its γ_s to γ_0 phase transformation and its nonlinear load and off-load behavior the mulberry composition may not be the optimum. Future study should be directed to other compositions.
- Tests should be conducted to determine the Bauschinger effect in mulberry. The nonlinear low strain behavior of mulberry should produce a large Bauschinger effect.
- Acoustic emission techniques appear to have successfully detected the phase transformation of type C alloy. This technique should be applied to other heat treatments and compositions.
- More compression tests should be conducted. Acoustic emission techniques should be used in these tests to compare the phase transformation in tension with compression.
- There should be microscopic observation of structure during tensile deformation of flat polished specimens. This should indicate if reversible twinning occurs.
- More tests should be conducted at both high and low temperatures. If the ordering process is diffusion controlled, it should be temperature dependent. Thus, changing temperatures is an excellent way of studying this process.

Acknowledgments

It is hoped that this test program will continue under the guidance of D.H. Wood, A. Goldberg, M.W. Guinan, and A.K. Mukherjee, all of whom helped in planning these various tests, analyzing test results and forming the conclusions drawn. Special acknowledgment is given to R.G. Stone for backing this project through engineering research. Finally, we extend our appreciation to F.A. Dishong for his efficiency and diligence in heat treating our specimens.

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