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STRAIN DIAGRAMS FOR URANIUM AND ITS ALLOY WITH MOLYBDENUM IN DYNAMIC UNIAXIAL COMPRESSION AND TENSION AND AT ELEVATED TEMPERATURES

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Systematic results from studies of dynamic diagrams of uniaxial compression and tension of uranium-238 and its alloy with molybdenum at various strain rates and temperatures are presented. The data allow one to plot stress curves versus strain, strain rate, and temperature for uniaxial compression–tension and to develop mathematical models describing the behavior of materials under various loading conditions most completely.

Introduction. Active investigation of the properties of uranium began with the development of nuclear weapons [1–3]. A great body of information on the static mechanical properties of uranium and its alloys is contained in [1–3]. It is established that some physical properties of uranium practically do not depend on its purity, microstructure, and method of processing. Among such properties are density, specific heat, thermal conductivity, etc. [1, 2]. For the three available allotropic forms of uranium, the following temperatures of phase transformations were detected: 670, 770, and 1130°C [3].

The mechanical properties of uranium are substantially anisotropic and depend strongly on the type of thermomechanical treatment and the mass fraction of the impurity. Polycrystalline uranium has a coarse-grained structure (the grain size reaches 3 mm) and shows all the mechanisms of plastic deformation typical of metals such as twinning, slip, and lines of fracture [1–3]. According to the data of [3], in static tension and at 20°C, the yield strength of uranium can vary from 180 to 600 MPa. Special features of uranium are viscous deformation, nonlinear resistance to deformation, and creep at elevated temperatures. The high sensitivity of uranium to various factors is responsible for the considerable difference of results obtained by different authors.

Doping of uranium by molybdenum makes the grains finer, improves the microstructure, and enhances and stabilizes the strength properties. The maximum increase in the strength properties of the alloys is observed when the mass fraction of molybdenum is 5–6% [1–3]. Increasing the mass fraction of molybdenum increases the resistance of alloys to corrosion and creep.

A number of data have been obtained for the dynamic mechanical characteristics, for example, results of complex experiments on shock compressibility and spall strength of uranium under shock-wave loading. In addition, the permanent elongation at rupture [3–5], the yield strength [4, 6], and the ultimate strength [5] of uranium and some of its alloys under dynamic-loading conditions were determined at different strain rates and temperatures (but, as a rule, without variation in one of these parameters). At the same time, the available data on the dynamic σ–ε diagrams of uranium are of a fragmentary nature and have been obtained without temperature variation [3, 4]. In addition, some other characteristics of uranium under dynamic loading, in

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particular, the Baushinger effect and the resistance to crack, have not been studied.

1. Experimental Procedure. We employ the well-known method of Hopkinson split bars (HSB), which is of widely used currently in dynamic tests of materials in compression, tension, torsion, and simultaneous torsion and compression (tension) [7, 8]. In addition, the compact scheme of the method turned out to be convenient for tests of toxic and radioactive materials [9]. The main characteristic of this method is the constant strain rate in experiments $\dot{\varepsilon} = \text{const}$, which is an apparent advantage for various types of data processing, including comparative analysis and simulation.

In the present paper, we describe only the special features of the procedure [9]. Generation of pressure pulse at the free end of the loading bar was performed by an explosive method with compression of a perforated damper made of an alloy of aluminum with manganese. The pressure pulses had a duration of 120–200 μsec and were similar in shape to a trapezoid with a front time of 40–50 μsec. In this case, the pressure waves that arise were 600–1000 mm in length, which far exceeded the specimen length [10]. The strain rate was changed by changing the damper geometry and the weight of the explosive.

In compression tests, we used the classical scheme first proposed by G. Kol'skii. The test samples were solid cylinders with dimensions of $a \times b = 8 \times 8$ mm (a is the diameter and b is the length), and the loading and steadying bars were made of hardened ShKh15 steel and had dimensions $a \times b = 12 \times 600$ mm. Computations showed that at the indicated ratio of the diameter to length of the specimen, the stress distribution over its cross-sections was nearly uniform.

In dynamic tension tests, we used a loading bar made of hardened 30 KhGSA steel with dimensions of $a \times b = 13.6 \times 500$ mm and a steadying bar of the same steel in the shape of a tube with dimensions of $a \times b = 20 \times 400$ mm. The specimens were of the reversible type and had the shape of a thimble $a \times b = 20 \times 18$ mm (the working section was 10 mm long and 1 mm thick).

Experiments at elevated temperatures up to 600°C were performed with a small electric furnace enclosing the bars in a common case [9]. A feature of the experiments was that the specimens were heated at a distance of about 150 mm from the measuring bars. After attainment of the required temperature, the specimen was remotely put in position between the bars and is automatically loaded. The delay from the moment the specimen comes in contact with the bars to the beginning of loading is about 0.02 sec. The temperature field of the specimen practically does not change in this time because of the contact thermal resistance. A copper screen was placed between the specimen and the heating coils to produce a uniform temperature field of the specimen, and the specimen was allowed to stay at a specified temperature of the experiment for 5–7 min. The heating temperature was monitored by a Chromel–Copel thermocouple. With a power of the electric furnace of 1 kW, the heating rate was about 1°C/sec [10].

Heating was performed only for experiments on dynamic compression. In tension experiments, the specimens were heavier and had a complex configuration, and this did not permit us to perform temperature tests in the formulation described above with remote delivery of heated specimens to the working position.

We note that without considerable corrections for the change in the elastic properties of the material of the bars, it is possible to perform tests of specimens in the working position between the bars under steady heating in the furnace to 200–400°C [10, 11]. However, in dynamic tension tests, the working section of the specimen in relation to the furnace is located between the solid loading and the tubular steadying bars, and this complicates both measurements and computations of the specimen temperature.

The σ–ε diagrams were plotted using the theory of elastic stress waves by processing the strain pulses recorded on the bars [7, 10]. The error in determining stresses and strains using the method described is about 12% [10].

2. Results of Investigation. In the present paper, the strain rate $\dot{\varepsilon}$ denotes the value on the plastic segment of the strain diagrams. The strain diagrams are given in the coordinates stress intensity–strain intensity σ_i–ε_i and are obtained by conversion of σ–ε diagrams in conditional coordinates using the well-known relations in [12], which take into account the change in the effective Poisson's ratio μ in the region of elastoplastic transition:

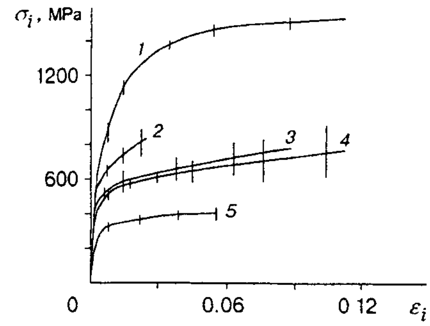

Fig. 1. Dynamic compression diagrams for uranium: 1) $\dot{\varepsilon}$ = 1300–1600 sec^{-1} and T = 20°C; 2) $\dot{\varepsilon}$ = 100–420 sec $^{-1}$ and T = 20°C; 3) $\dot{\varepsilon}$ = 520–1040 sec $^{-1}$ and T = 100°C; 4) $\dot{\varepsilon}$ = 160–1440 sec^{-1} and T = 200°C; 5) $\dot{\varepsilon}$ = 540–890 sec^{-1} and T = 400°C.

$$\sigma_i = \sigma/[1 - \mu' \ln(1+\varepsilon)]^2, \qquad \varepsilon_i = (2/3)(1+\mu')\ln(1+\varepsilon),$$

where $\mu' = 1/2 - (1/2)(\sigma/(E\varepsilon))(1 - 2\mu)$.

The spreads of the values of σ_i indicated in the σ_i–ε_i diagrams and the intervals of spread of the mean values of the dynamic yield strengths $\sigma_{-0.2}$ and $\sigma_{+0\,2}$ and the strength $\sigma_{+\mathrm{time}}$ are determined with a confidence probability of 0.95.

Compression of Uranium Specimens. In dynamic compression tests, we used specimens manufactured of cast bars. The test temperature was T = 20–400°C and the strain rate was $\dot{\varepsilon}$ = 100–1600 sec^{-1}. Figure 1 gives averaged compression diagrams σ_i–ε_i for uranium at various T and $\dot{\varepsilon}$. The diagrams are plotted with averaging of the results of 4–9 experiments.

It can be seen in Fig. 1 that at a temperature of 20°C, the σ_i–ε_i diagrams are nonlinear, and the dynamic strain hardening depends strongly on $\dot{\varepsilon}$. The yield strength depends weakly on $\dot{\varepsilon}$. Similar data obtained by Maiden for cast uranium at T = 20°C are given in [3].

Tests of uranium at $T \geqslant 100$°C showed loss of stability of the uniform plastic deformation process and formation of defects of the "orange peel" type on the generatrix surfaces of the specimens. According to [13], such defects appear on metal specimens with grain sizes larger than 50 μm. Microstructural studies of the uranium specimens showed that the average grain size was 0.2 mm. Deformation of the material proceeded by both twinning and slip with a complex distribution of grains over the volume of the specimen. Because of the loss of stability, the compression diagram and the yield strengths do not depend on $\dot{\varepsilon}$ and have a considerable experimental spread. At the same time, increasing the temperature decreases the deformation hardening of uranium and the nonlinearity of the diagrams (Fig. 1).

The averaged dynamic yield strengths $\sigma_{-0.2}$ of uranium corresponding to diagrams 1–5 in Fig. 1 are (660 ± 80), (565 ± 42), (446 ± 48), (440 ± 30), and (300 ± 13) MPa. The temperature dependence of the dynamic yield strength is shown in Fig. 2.

Little information on the static compression of uranium, in particular at different temperatures, can be found in the literature. Emel'yanov and Evstyukhin [1], referring to the data of foreign authors, note that for uranium at 100–750°C with two degrees of prestrain: $\sigma_{-0.2}$ = 620–770 MPa at T = 100°C, $\sigma_{-0.2}$ = 480–665 MPa at T = 200°C, and $\sigma_{-0.2}$ = 270–370 MPa at T = 400°C.

For cast uranium at T = 20°C and $\dot{\varepsilon}$ = 1000 sec^{-1}, the value of $\sigma_{-0.2}$ = 670 MPa, obtained in [6] by the HSB method, is in good agreement with our data, and in [3], the value of $\sigma_{-0.2}$ = 380 MPa (we determined from the σ–ε diagrams) differs by a factor of 1.7.

Tension of Uranium Specimens. In dynamic tension experiments, we used specimens of cast bars. At $T \cong 0$°C, the strain rate was 1000 sec^{-1}. Figure 3 shows the σ_i–ε_i tensile diagram averaged over five experiments. Similarly to the compression diagrams (see Fig. 1), the tensile diagram in Fig. 3 shows nonlinear resistance to deformation. Under the loading conditions indicated, the plasticity of uranium is rather low,

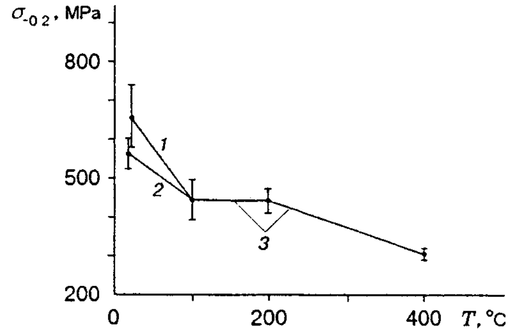

Fig. 2

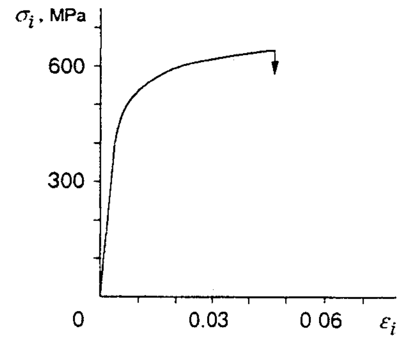

Fig. 3

Fig. 2. Temperature dependence of dynamic yield strength $\sigma_{-0.2}$ for uranium: segments 1, 2, and 3 refer to $\dot{\varepsilon} = 1300$–1600, 100–420, and 160–1440 sec^{-1}, respectively.

Fig. 3. Dynamic tensile diagram for uranium at $T \cong 0$°C and $\dot{\varepsilon} = 1000$ sec^{-1}.

and at a strain of 4.0–4.2%, the specimens undergo rupture. In this case, the average yield strength is $\sigma_{+0.2} = (470 \pm 78)$ MPa and the average ultimate strength is $\sigma_{+\text{time}} = (650 \pm 83)$ MPa. For uranium bars from the same batch in static tension and at $T = 20$°C, we obtained $\sigma_{+0.2} = 350$ MPa, $\sigma_{+\text{time}} = 606$ MPa, and the permanent elongation at rupture $\delta = 5.3\%$.

According to the data of [1, 3], for uranium at $T = 20$°C and in static tension, $\sigma_{+0.2} = 180$–600 MPa, $\sigma_{+\text{time}} = 380$–$1000$ MPa, $\delta = 1.2$–35%.

Data on the dynamic tension of uranium can be found in [3, 4]. For rolled and then annealed α-uranium, the values of δ at $T = 20$–250°C and $\dot{\varepsilon} = 150$ sec^{-1} are presented in [3]. According to the data of [3], $\delta = 4$–8% at standard temperature. In [4], tensile diagrams σ–ε for α-uranium in the initial and annealed states were obtained for $T = 20$°C and $\dot{\varepsilon} = 10^{-4}$–$2.5 \cdot 10^3$ sec^{-1}. Experiments at $\dot{\varepsilon} > 5 \cdot 10^2$ sec^{-1} were performed by the HSB method. The diagrams are nonlinear. According to [4], for the indicated materials at $\dot{\varepsilon} = 1400$–1600 sec^{-1}, the yield strength was $\sigma_{+0.2} = 500$–650 MPa and the permanent elongation was $\delta = 12$–18% [while the values computed from $\delta = \delta(\dot{\varepsilon})$ diagrams can differ by a factor of 1.7].

The results given above indicate that the instability of the mechanical properties of uranium in tension and compression, which is typical of static tests, is manifested in dynamic tests too. In this case, nonlinear resistance of uranium to plastic deformation is observed.

Compression of Specimens of Uranium Doped with Molybdenum. In dynamic compression experiments, we tested uranium specimens doped with molybdenum (mass fraction 1.3%) manufactured from cast bars. The test temperature was $T = 20$–600°C and the strain rate was 200–1800 sec^{-1}. Figure 4 shows averaged compression diagrams σ_i–ε_i of the alloy at various T and $\dot{\varepsilon}$. Each diagram is averaged over the results of 2–6 experiments. In the case of two experiments, the arithmetic mean value was determined. The plastic segments of the σ_i–ε_i diagrams of the alloy at $T = 20$–200°C are of a weakly nonlinear nature, which is less pronounced than that for uranium (see Fig. 1). At $T = 400$–600°C, nonlinearity is not manifested. The dynamic deformation hardening of the alloy decreases with increase in temperature, and at $T = 600$°C, it is practically absent. The averaged dynamic yield strengths $\sigma_{-0.2}$ of the alloy corresponding to diagrams 1–12 in Fig. 4 are (990 ± 70), (868 ± 54), 760, (720 ± 67), (665 ± 18), (580 ± 30), (500 ± 35), (426 ± 52), (370 ± 40), (360 ± 26), 330, and (275 ± 35) MPa. Figure 5 gives the temperature dependences of $\sigma_{-0.2}$, which demonstrate that $\sigma_{-0.2}$ generally decreases linearly with increase in T.

The experiments were conducted for the following three ranges of strain rate: $\dot{\varepsilon} = 200$–520, 600–1000, and 1000–1800 sec^{-1}, in which the characteristic properties of the alloy were manifested. Figure 5 shows the dependences for the 1st and 3rd ranges (curves 2 and 1, respectively). The dependence for the 2nd range is

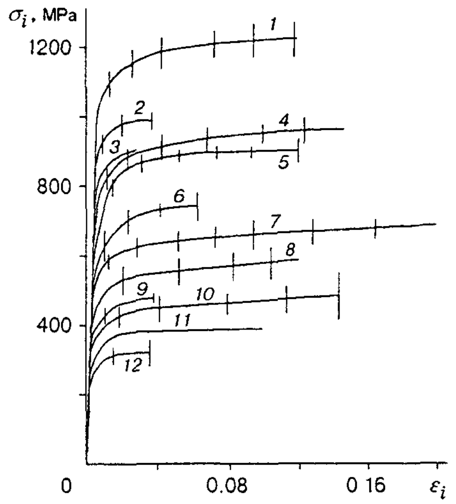

Fig. 4

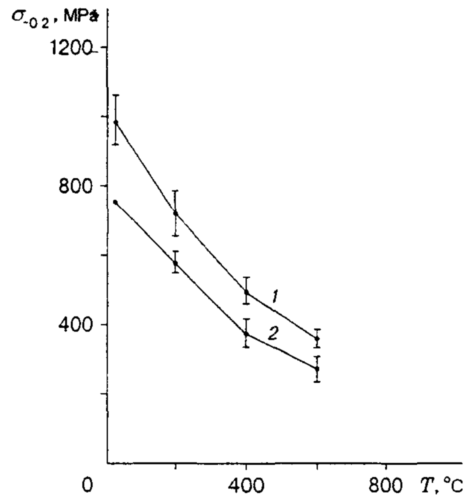

Fig. 5

Fig. 4. Dynamic compression diagrams of uranium doped with molybdenum (mass fraction 1.3%): 1) $\dot{\varepsilon}$ = 1000–1400 sec^{-1} and T = 20°C; 2) $\dot{\varepsilon}$ = 600–880 sec^{-1} and T = 20°C; 3) $\dot{\varepsilon}$ = 280–360 sec^{-1} and T = 20°C; 4) $\dot{\varepsilon}$ = 1300–1800 sec^{-1} and T = 200°C; 5) $\dot{\varepsilon}$ = 800–1100 sec^{-1} and T = 200°C; 6) $\dot{\varepsilon}$ = 350–510 sec^{-1} and T = 200°C; 7) $\dot{\varepsilon}$ = 1200–1700 sec^{-1} and T = 400°C; 8) $\dot{\varepsilon}$ = 800–1000 sec^{-1} and T = 400°C; 9) $\dot{\varepsilon}$ = 200–520 sec^{-1} and T = 400°C; 10) $\dot{\varepsilon}$ = 1200–1400 sec^{-1} and T = 600°C; 11) $\dot{\varepsilon}$ = 850–1000 sec^{-1} and T = 600°C; 12) $\dot{\varepsilon}$ = 200–500 sec^{-1} and T = 600°C.

Fig. 5. Temperature dependence of the dynamic yield strength $\sigma_{-0.2}$ of uranium doped with molybdenum (mass fraction 1.3%): curves 1 and 2 refer to $\dot{\varepsilon}$ = 1000–1800 and 200–520 sec^{-1}, respectively.

intermediate between the first two and is not given in Fig. 5.

From the results obtained it follows that at each of the test temperatures, as the $\dot{\varepsilon}$ increases from the 1st range to the 2nd range and from the 2nd to the 3rd, the value of $\sigma_{-0.2}$ increases by a factor of 1.1–1.2 , which indicates a linear dependence of $\sigma_{-0.2}$ on $\dot{\varepsilon}$.

No characteristics of uranium doped with molybdenum in static compression are available in the literature. However, in static tension at T = 20–600°C (see [14]) for uranium doped with molybdenum (mass fraction 9.2%), the decrease in $\sigma_{+0.2}$ with increase in T is generally linear. For variously manufactured alloys of uranium with molybdenum (mass fraction 10%) in dynamic tension at $\dot{\varepsilon}$ = 20–100 sec^{-1} and T = 20–320°C (see [5]), the value of $\sigma_{+\text{time}}$ increases linearly and decreases linearly with increase in $\dot{\varepsilon}$ and T, respectively. Thus, the data of [5, 14] are in good agreement with our data (Fig. 5).

Dynamic compression data for an alloy of uranium with molybdenum are given in [6]. Here for a cast alloy with molybdenum (mass fraction 2.2%) at T = 20°C and $\dot{\varepsilon}$ = 1000 sec^{-1}, a value of $\sigma_{-0.2}$ = 1050 MPa is obtained, which is in good agreement with our data.

Tension of Specimens of Uranium Doped with Molybdenum. In dynamic tension experiments, we used specimens of uranium doped with molybdenum (mass fraction 1.3%) manufactured from cast bars. At $T \cong$ 0°C, the strain rate was 1200 sec^{-1}. Figure 6 gives a σ_i–ε_i tensile diagram averaged over four experiments, in which the plastic deformation segment shows linear hardening. Under the indicated conditions, the specimens broke at δ = 15%. In this case, the average yield strength $\sigma_{+0.2} = (900 \pm 56)$ MPa and the ultimate strength $\sigma_{+\text{time}} = (1080 \pm 62)$ MPa. For specimens of this alloy from the same batch in static tension at T = 20°C, we obtained $\sigma_{+0.2}$ = 620 MPa, $\sigma_{+\text{time}}$ = 910 MPa, and δ = 19%.

According to [15], in static tension and at T = 20°C, for alloys of uranium with a similar content of molybdenum (mass fraction 2%) but with different composition and different thermal treatment, $\sigma_{+0\,2}$ = 400–1350 MPa, and $\sigma_{+\text{time}}$ = 770–1350 MPa, δ = 0.2–21%. In static loading of an alloy of uranium with

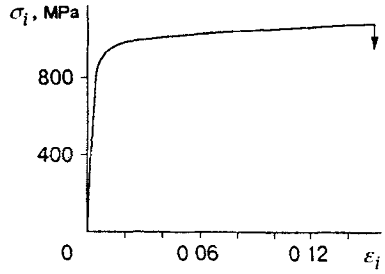

Fig. 6. Dynamic tensile diagram for uranium doped with molybdenum (mass fraction 1.3%) at $T \cong 0°C$ and $\dot{\varepsilon} = 1200$ sec^{-1}.

molybdenum (mass fraction 10%) under similar conditions, Hoge [5] obtained $\sigma_{+\text{time}} = 820$–1180 MPa and $\delta = 5$–23%.

Data on dynamic tension of alloys of uranium with molybdenum for various $\dot{\varepsilon}$ and T can be found, as was already noted, in [5]. In particular, for an alloy with molybdenum (mass fraction 10%) at $\dot{\varepsilon} = 100$ sec^{-1}, the following values were obtained: $\sigma_{+\text{time}} = 1610$ MPa and $\delta = 6.3\%$ at $T = 20°C$ and $\sigma_{+\text{time}} = 1200$ MPa and $\delta = 9\%$ at $T = 320°C$.

Conclusion. Experimental data of scientific and practical interest were obtained for the dynamic mechanical characteristics of cast uranium and its alloy with molybdenum. It is established that in dynamic compression of the alloy at $T = 20$–600°C, in contrast to undoped uranium at $T = 100$–400°C, the yield strength depends on $\dot{\varepsilon}$.

The data obtained for uranium and its alloys with molybdenum show that the addition of molybdenum enhances the strength properties of uranium in both static and dynamic tension or compression. In addition, at the same temperatures and rate of loading, the alloys have more stable mechanical characteristics, as confirmed, for example, by the nature of the σ_i–ε_i strain diagrams obtained.

Since, in practice, tension is most critical in most cases, it is necessary to extend the knowledge of dynamic tensile diagrams for uranium and its alloys, in particular, at elevated temperatures.

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