

tronics model 547 oscilloscope, and X and Y cut quartz driver and detector crystals.

Low temperatures were measured using a calibrated copper-constantan thermocouple, while high temperatures were measured using a chromel-alumel thermocouple. The temperature ranges of the two apparatus overlapped so that an internal check on the instruments and specimens was provided.

DATA TREATMENT

The experimental data were treated in much the same way as the work on niobium reported earlier by the authors.⁴ Briefly, plots were made of the fundamental resonance frequency vs temperature for both the longitudinal and torsional vibration modes for each of the four crystals over the temperature range from -200°C to approximately 660°C. Resonance frequencies were then determined graphically for both vibrational modes of each crystal at 20°C intervals. This method circumvented the necessity of taking the measurements on each crystal at exactly the same temperature.

Corrections for changes in the length and density of the specimen were made using a mean linear thermal expansion coefficient of 5.31×10^{-6} per °C. Knowing the temperature, resonance frequency, specimen length and density, and the thermal expansion coefficient, the moduli were calculated from the following equation:

$$\text{Modulus } (E \text{ or } G) = 4l^2 f^2 \rho (1 + \alpha \Delta T)^{-1},$$

where f is the resonance frequency, longitudinal if E is being calculated and torsional if G is being calculated, l is the specimen length, ρ is the specimen density, α is the thermal expansion coefficient, and ΔT is the difference between 25°C and the temperature. Using cgs units the modulus is given in $\text{dyn} \cdot \text{cm}^{-2}$.

The calculated values of Young's and shear moduli were combined with the measured orientation functions to calculate the elastic stiffness coefficients. The calculations were made on a computer using a least

TABLE II. Chemical analysis of Mo specimens.

	Semi-Element crystals (ppm)	Linde crystals (ppm)
O ₂	40 to 80	10 to 30
N ₂	40	30
C	30	30
Ni	30	<10
Cu	5	<3

⁴ P. E. Armstrong, J. M. Dickinson, and H. L. Brown, Trans. AIME 236, 1404 (1966).

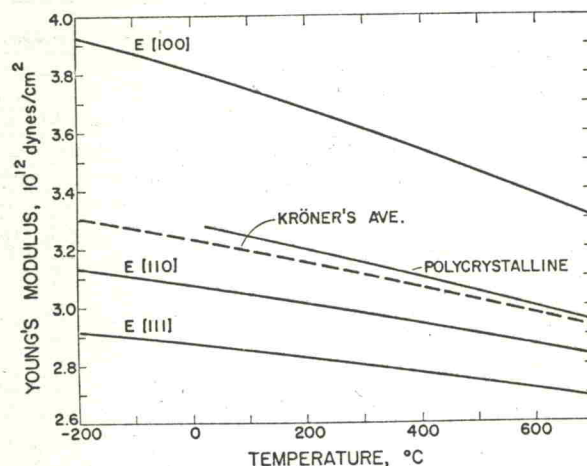


FIG. 1. The variations with temperature of Young's modulus of three single crystals of molybdenum, Young's modulus of fine-grained polycrystalline molybdenum, and Young's modulus calculated for isotropic molybdenum from the single-crystal data.

squares fitting program with Eqs. (1) and (2):

$$E^{-1} = - \{ [2 / (C_{11} - C_{12})] - C_{44}^{-1} \} \Phi + \frac{1}{3} \{ [2 / (C_{11} - C_{12})] + (C_{11} + 2C_{12})^{-1} \} \quad (1)$$

$$G^{-1} = 2 \{ [2 / (C_{11} - C_{12})] - C_{44}^{-1} \} \Phi + [C_{44}^{-1}]. \quad (2)$$

Since data from four crystals were used, eight equations in three unknowns could be fitted at each temperature and a reasonable estimate of the standard deviation of each of the elastic constants could be obtained.

From the calculated C_{ij} 's other parameters were determined using Zener's notation as:

$C \equiv C_{44}$ —the coefficient indicating resistance to shear between (100) planes in the [010] direction.

$C' = (C_{11} - C_{12})/2$ —the coefficient indicating resistance to shear between (110) planes in the [110] direction.

$K = (C_{11} + 2C_{12})/3$ —the bulk modulus.

$A = C/C'$ —the anisotropy ratio.

RESULTS

The results of this investigation have been presented as a series of graphs. These graphs, Figs. 1 to 8, have been plotted to the same scale so that the slopes are directly comparable by observation.

As is normal for most metals in this temperature range, Young's modulus and shear modulus decreased almost linearly with increasing temperature, as shown in Figs. 1 and 2. The change in Young's modulus with temperature was largest for the [100] direction, dropping nearly 16% over the 860°C temperature range while the change was about 8% for the [111] direction. The shear modulus for the [111] direction decreased 14% while the decrease was 8% in the

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