Temperature Dependence of the Elastic Constants of Molybdenum*

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The elastic properties of molybdenum single crystals have been measured using thin-rod resonance techniques as a function of temperature from −198° to over +650°C. Molybdenum behaves in a normal manner over this temperature range. Its elastic stiffness coefficients, with the exception of C_{12} which increased 3%, decreased in a nearly linear manner. The decrease was 8% for C_{44}, 11% for C_{11}, and 18% for C'. From these data the temperature dependence of the bulk modulus, the shear coefficient C', the anisotropy ratio, and the Young's and shear modulus of isotropic polycrystalline molybdenum were calculated.

INTRODUCTION

THE elastic behavior of molybdenum is of interest because of the importance of this metal in modern technology. Molybdenum is also one of the few pure cubic metals whose resistance to elastic shear deformation across (100) planes is less than that across (110) planes, resulting in values less than unity for the anisotropy factor as defined by Zener.[1] The same relative change in magnitude of the shear elastic constants with temperature for crystals with anisotropy factors less than or greater than unity produces distinctly different changes in elastic stiffness coefficients for dilational deformation modes. In the case of niobium metal, for example, the authors[2] have shown that Young's modulus measured in directions other than [100] actually increased with temperature, over at least a 1100°C temperature range. The purposes of this investigation were, then, twofold: first, to extend the temperature range of previously reported measurements, and second, to detect the presence of any anomalies at elevated temperatures that might be comparable to the behavior of niobium.

EXPERIMENTAL PROCEDURE AND SPECIMEN PREPARATION

Single crystals of electron-beam-melted molybdenum metal were obtained from Semi-Elements Inc. in the form of rods, approximately 0.6-cm-diam by 13-cm-long. These crystals were ground to a uniform diameter (±0.001-cm) and cut to 10-cm lengths. The ends were ground flat and parallel using metallographical procedures. After a light chemical etch (HNO_3+HF) the crystals were annealed 2 h at 2100°C in a vacuum of 1×10^{-6} Torr and furnace cooled.

The orientation function, $\Phi=\alpha^2\beta^2+\alpha^2\gamma^2+\beta^2\gamma^2$ where α, β, and γ are the direction cosines of the sample rod axis, was determined for each molybdenum crystal using standard x-ray diffraction methods. The crystals had either the [100], [110], or [111] nearly parallel to their cylinder axis. The orientation functions of these crystals are shown in Table I.

A single crystal of molybdenum 1.6-cm diameter by 12 cm long was obtained from the Linde Company. The rod axis was between the [100] and [110]. Two specimens approximately 1-cm-thick were prepared from this rod, one having parallel faces cut perpendicular to a [100] and the other having parallel faces cut perpendicular to a [110].

Chemical analyses were performed on the specimens using standard spectrographical techniques except that oxygen was determined by vacuum fusion, nitrogen by a modified Kjeldahl method, and carbon by combustion. The results are given in Table II. Elements not shown in Table II were below normal limits of detection.

TABLE I. Crystallographic orientation of molybdenum specimens.

Crystal	Cylinder axis direction	Φ
Semi-Elements *a*	[100]	0.0047
Semi-Elements *b*	[100]	0.0015
Semi-Elements *c*	[110]	0.251
Semi-Elements *x*	[111]	0.331

MEASUREMENTS OF ELASTIC PROPERTIES

The data necessary to determine the elastic properties of molybdenum were obtained from the thin-rod free-free resonance measurements using instrumentation described previously by the authors.[3] A separate instrumentation package also employing capacitive probes for the excitation and detection of longitudinal resonances and eddy-current probes for the excitation and detection of torsional resonances was constructed to fit in a cryostat for measurements below room temperature.

High-frequency pulse-transmission techniques were used with the Linde crystals at room temperature. Measurements were made at 10 Mc/sec employing an Arenberg model 650 PG pulsed oscillator, a Tek-

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[1] C. Zener, *Elastic and Anelasticity of Metals* (Univ. of Chicago Press, Chicago, Ill., 1948).
[2] P. E. Armstrong and H. L. Brown, Trans. ASM 58, 30 (1965).
[3] P. E. Armstrong and J. M. Dickinson, Rev. Sci. Inst. 36, 1719 (1965).