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ELASTIC MODULI AND ULTRASOUND VELOCITIES OF TUNGSTEN AS A FUNCTION OF TEMPERATURE

by

Ronald G. Peterson

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Metallurgy Division

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ELASTIC MODULI AND ULTRASOUND VELOCITIES OF TUNGSTEN AS A FUNCTION OF TEMPERATURE

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ABSTRACT

The results of a preliminary study of the elastic moduli and the ultrasound velocities of tungsten are given. The data were obtained by an ultrasonic pulse-echo method.

INTRODUCTION

This report presents the results of a preliminary study of the ultrasound velocities and the elastic moduli of tungsten as a function of temperature. These parameters were determined from room temperature to 1480°C. The measurements, on specially fabricated tungsten samples, were made by an ultrasonic pulse-echo method. This report briefly discusses the technique and the equipment used and compares the data with the results obtained by other investigators.

TECHNIQUE AND EQUIPMENT

A facility for determining the sound velocities and elastic moduli has been reported previously.¹ The previous report also contains a detailed discussion of the relationship between ultrasonic pulse velocities and the elastic moduli, as well as the techniques of transit-time and delay-time measurements from which the sound velocities were calculated. In an isotropic material, there are two independent sound velocities, the longitudinal-wave velocity and the shear-wave velocity, and there are unique relationships between these velocities and any two independent elastic moduli. This report gives values for Young's modulus, shear modulus, and Poisson's ratio for tungsten. Once two of the properties are known, the third can be determined.

The vacuum furnace described in Ref. 1 was used for measurements of the parameters of tungsten up to 910°C. At that temperature, the furnace was operating at full power and the maximum temperature was determined by the thermal conductivity of the sample. For higher temperature measurements, a different type of furnace was used. (A cross-sectional view of this type of furnace is shown in Fig. 1.) The specimen is cooled by direct contact

with water passing through a cooling jacket located inside the vacuum chamber. This coolant jacket was also used in the lower-temperature furnace. In both furnaces, the jacket was sealed to the same area of the specimen. The specimen was machined so that it could be mounted in either furnace, as shown in Fig. 1 of this report, and in Fig. 5 of Ref. 1.

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Fig. 1. Cross Section of Furnace Used for Higher-temperature Measurements

easily. Since the specimen had polished ends, it was assumed that the spectral emittance was 0.43,² and the "brightness" temperature was converted to "true" temperature on this basis.

The furnace, made by Richard D. Brew and Co., Inc., for use with an Instron mechanical testing device, was modified to accommodate the mirror assembly and to provide the specimen mounting flange. The specimen was heated by a tantalum-sheet heater mounted in a water-cooled "clamshell" assembly. Since the "clamshell" halves did not quite meet at the bottom, parts of the end and shoulder of the rod could be seen by means of the mirror system. To prevent the formation of deposits on the mirror, a protective vane (not shown in Fig. 1) could be slid over the mirror.

Measurements were made to 1480°C in the high-temperature furnace. At that temperature, the top end of the rod (where the ultrasound transducer was coupled to the specimen) was warm to the touch. Above this temperature, the rod was too hot to touch.

An arrangement for measuring the temperature of the shoulder and of the end of the rod is shown in Fig. 1. A stainless steel mirror reflects the light from the bottom of the specimen through a sight glass and out of the furnace, where the light is observed through a Leeds and Northrup Optical Pyrometer (disappearing-filament type). The pyrometer was calibrated by viewing a standard tungsten lamp (calibrated by the National Bureau of Standards) through the same mirror-and-sight-glass arrangement. The "brightness" temperature of the specimen could be determined

MEASUREMENTS ON THE SPECIMEN

The tungsten specimen used for this study was supplied by the General Electric Company, Lamp Metals and Components Department, Cleveland, Ohio. The specimen was a solid, round bar 38 cm long with a 2.47-cm nominal diameter. The bar had been fabricated by powder-metallurgy techniques and was swaged after it had been pressed and sintered. The swaging produced a rod that was worked to a minimum of 75%

reduction in area; a density of $19.2 \pm 0.05 \text{ gm/cm}^3$ was assumed for the specimen. Table I presents an analysis of the impurities in the rod. Table II lists values of longitudinal-sound-wave velocity, shear-wave velocity, Young's modulus, shear modulus, and Poisson's ratio at several different temperatures, as

calculated from our measurements. Also shown is the difference between the temperature of the shoulder of the rod and the temperature of the end of the rod. As discussed in Ref. 1, a large thermal gradient usually exists in the end of the rod in the low-temperature furnace. Such a gradient existed in the high-temperature furnace also, but the gradient was not as large as that in the low-temperature furnace. The values for temperature difference (Table I) also include uncertainties in calibration and in reproducibility of pyrometer readings. The values for the velocities and elastic moduli obtained in the ANL study are plotted in Figs. 2 and 3. The lengths of the horizontal line through each point denote the magnitude of the temperature difference discussed above.

TABLE I. Impurities in the Tungsten Rod

Fe	< 20 ppm by weight	Ni	< 10 ppm
Mo	40 ppm	C	50 ± 10 ppm
Ca	< 3 ppm	O ₂	25 ± 10 ppm
Cr	< 10 ppm	N ₂	1 ppm
Cu	< 10 ppm	H ₂	2 ppm
Al	< 10 ppm		

TABLE II. Sound Velocities and Elastic Moduli of Tungsten

Temperature, °C	Temperature Difference, °C	Longitudinal Velocity, 10^5 cm/sec	Shear Velocity, 10^5 cm/sec	Young's Modulus, $10^{11} \text{ dynes/cm}^2$	Shear Modulus, $10^{11} \text{ dynes/cm}^2$	Poisson's Ratio
First heating						
25.6	0.1	5.24	2.81	39.3	15.2	0.298
392	38	5.14	2.75	35.6	14.5	0.298
599	46	5.09	2.71	36.7	14.0	0.302
882	51	5.05	2.69	35.7	13.7	0.303
908	53	5.05	2.65	34.9	13.3	0.311
After cooling to room temperature and reheating; second heating						
725	47	5.08	2.72	36.0	14.1	0.299
301	23	5.17	2.81	39.0	15.1	0.290
497	35	5.16	2.75	37.6	14.4	0.301
210	16	5.19	2.83	39.5	15.3	0.289
903	55	5.07	2.69	35.8	13.7	0.305
After cooling to room temperature and mounting in other furnace; third heating						
1007	40	5.08	2.67	35.2	13.5	0.309
1293	40	5.01	2.60	33.5	12.7	0.316
1482	40	4.92	2.58	32.8	12.5	0.310
After cooling to room temperature						
25	0	5.35	2.75	38.3	14.5	0.321

Fig. 2. Sound Velocities in Tungsten as a Function of Temperature

Fig. 3. Elastic Moduli of Tungsten as a Function of Temperature

To calculate high-temperature moduli, the thermal expansion of the rod must be considered.¹ The average values from several determinations of the rod expansion were averaged.³⁻⁶

COMPARISONS WITH OTHER INVESTIGATIONS

Several groups of investigators have measured the elastic moduli of tungsten. The results determined at ANL will be compared only with the results obtained through the use of so-called "dynamic" methods. The dynamic techniques involved correlations of the parameters that describe mechanical vibrations with the elastic moduli, and are distinguished from static methods where the moduli are obtained by the use of a device such as a tensile testing machine. There are two common dynamic methods. In the resonant-bar method, the specimen, usually in the shape of a rectangular bar, is caused to vibrate continuously at its own natural resonant frequency or multiples of it. The elastic constants can be calculated if this procedure is carried out for at least two different modes of vibration. The second dynamic method is the pulse-echo method used at ANL for this study.

The elastic moduli of tungsten have been reported by several investigators⁷⁻¹² who used the resonant-bar method of measurement. Figures 2 and 3 compare the ANL data with the latest data from these studies.⁹⁻¹² Other investigators¹³⁻¹⁵ have also used the pulse-echo method, and the latest data^{14,15} are also plotted in Figs. 2 and 3.

Only Lowrie¹⁴ has given data for sound velocities. The values for longitudinal velocities obtained in the ANL study agreed with Lowrie's data, but the values for shear velocities were generally lower than Lowrie's values by about 2.5-3%. Lowrie's actual data points are not plotted; the points shown in Fig. 2 were selected from several places along the smooth curve that Lowrie fitted to his data. However, it appears from Lowrie's original data that the scatter in the points was approximately 0.2%, whereas the ANL data indicate a scatter of approximately 1.2%.

Lowrie and Gonas^{14,15} are the only investigators who indicate Poisson's ratio and the shear modulus. Since the value of shear velocity is greater than that obtained in the ANL study, the value of shear modulus must be greater and the Poisson ratio must be lower. All the investigators show values of Young's modulus. The points plotted (Fig. 3) for the data of Armstrong and Brown¹¹ and for Pisarenko *et al.*¹⁰ were taken from curves fitted through the actual data points; on the other hand, the actual data points of Hill and Shimmin⁹ and of Umekawa *et al.*¹² were plotted.

Two observations can be made: (1) The differences between the values of elastic moduli obtained at ANL and those of most of the other investigators (except Pisarenko *et al.*) indicate that the values of shear-wave velocities are lower than those of Lowrie and Gonas.^{14,15} If the values

obtained at ANL agreed with those of Lowrie,¹⁴ the elastic moduli values would then agree with most of the other values. There is no apparent reason why our shear-wave velocity values should be different. Corrections for any reasonable difference in density between the samples used by different investigators should not make a large difference in the velocity values, and, even so, both longitudinal- and shear-wave velocities would have been affected. (2) The values obtained at ANL show more scatter. This can be attributed to the poorly defined pulses in our echo pattern. For some reason, the leading edges of the pulses were not well defined at many temperatures. As discussed previously,¹ this can lead to an uncertainty in transit-time or in delay-time measurements and, consequently, to errors in velocity calculations.

FUTURE INVESTIGATION

A new high-temperature vacuum furnace has been obtained that will enable ultrasonic measurements to be made to at least 2700°C. The facility has been designed specifically for this type of measurement and will eliminate the large thermal gradients that heretofore have been present in the small-diameter section of the specimen. A new tungsten sample will be machined and measured in this furnace.

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