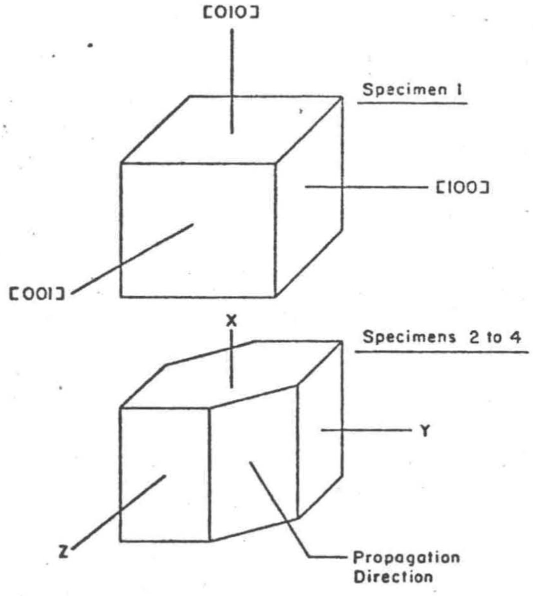

| Specimen | X | Y | Z |
|---|---|---|---|
| 2 | [001] | [010] | [100] |
| 3 | [100] | [010] | [001] |
| 4 | [010] | [100] | [001] |

Fig. 1. Orientation of specimens used for the elastic-constant measurements.

samples could be examined for consistency. Sample 2, which would have been used to determine the on-diagonal moduli corresponding to the [001] propagation direction, cleaved while it was being ground. As a result, further attempts at grinding the (001) face were not made. Specimens 3 and 4, however, were successfully prepared, and checks could be made on the elastic constants obtained from propagation directions parallel to [100] and [010].

All sample faces were oriented by using the Laue back-reflection technique and are accurate to better than 1°. The faces of the samples were ground flat by using #320 silicon carbide powder and were polished with 1-$\mu$ diamond paste. The sample faces were found to be parallel to within 0.0001 cm/cm and flat to within 0.0001 cm. Sample thickness was measured by using a Starrett 221 micrometer with a stated accuracy of ±0.00003 cm. The densities of the specimens were determined by using the usual liquid immersion method (Table 2). A mean density of 3.354 ± 0.002 g/cm³ was adopted for all calculations.

The adiabatic elastic constants and their temperature and pressure dependence were determined by measuring the transit times of 20-MHz ultrasonic waves between parallel faces by using the pulse superposition technique of *McSkimin* [1961]. Two different ultrasonic pulse superposition units, which have been designated MRL PSP AFC and Arenberg PSP AFC, were used in the present study. Unless it is otherwise specified, the MRL unit has been used to obtain the acoustic data presented in this study. A complete description of these units, including the automatic peak finder, which electronically detects the correct echo maximum, has been given in detail by other authors [*Gieske*, 1968; *Miller*, 1969]. The pressure apparatus has been described previously by *Bogardus* [1964].

For determining the zero pressure elastic constants and during the pressure tests, the temperature of the specimens was maintained at 25.0 ± 1.0°C by circulating water through a copper tubing jacket wrapped around the outside of the pressure vessel with a Lauda constant temperature circulator (model NBS-HT). The temperature and the temperature gradient of the specimens were monitored by two chromel-alumel thermocouples placed in proximity to two different faces of the specimen. The thermal emf's were measured before and after each measurement on a Leeds and Northrup K-3 potentiometer by using an ice bath reference, and a negligible temperature gradient was indicated within the specimens.

Pressure in the vessel was provided by compressing argon gas with a Harwood two-stage gas compressor system. The pressure in the test vessel was measured by a manganin cell in conjunction with a Carey-Foster bridge (model C, Harwood Engineering Company) calibrated prior to each pressure run.

The temperature dependence of the elastic constants was determined by using an internal furnace made of a cylindrically wound coil of

TABLE 2. Densitites of Bronzite Specimens at 25°C

| Specimen | Density, g/cm³ |
|---|---|
| 1 | 3.354 ± 0.001 |
| 2 | 3.355 ± 0.001 |
| 3 | 3.355 ± 0.001 |
| 4 | 3.351 ± 0.001 |
| Average | 3.354 ± 0.002 |

Kanthal wire that fits within the 2-inch diameter of the bore of the pressure vessel. By using the thermocouple arrangement described for the pressure tests, a maximum variation of ±1.5°C was maintained during all temperature measurements. To minimize the effects of oxidation of the bore and the sample-holding device, the system was purged with argon gas prior to each temperature run. Natural quartz ac- and cross-cut transducers having diameters of 0.250 inch and resonance frequencies of 20 MHz ± 1% (purchased from the Valpey Corporation, Holliston, Massachusetts) were used to generate and receive the transverse and longitudinal ultrasonic wave pulses, respectively. Two types of bonding materials were used to cement the transducers to the sample faces. At room temperature, for measuring the elastic constants and their pressure dependence, non-aq stopcock grease (Fisher Scientific Company) was used. For high-temperature measurements Extemp 9901 (Lubrication Engineering Company) was found to be satisfactory to approximately 350°C, at which point it became dry and was no longer functional.

## EXPERIMENTAL RESULTS

*Elastic constants at 25°C and 1 atm.* By using the orientations shown in Figure 1 and the equations of *Fisher and McSkimin* [1958], the adiabatic elastic constants $c_{\mu\nu}{}^S$ were determined (Table 3). The corresponding sample numbers, propagation directions **N**, and polarization directions **U** used to obtain the $c_{\mu\nu}{}^S$ are also included in this table. When it is considered that four different natural specimens were used, the consistency of the data is quite remarkable.

Because calculation of the cross-coupling moduli depends on the direction cosines of the propagation directions, it is necessary to determine these quantities accurately. They were determined by the method proposed by *Fisher and McSkimin* [1958]. Because each cross-coupling modulus may be determined by either a 'quasi-shear' or a 'quasi-longitudinal' elastic-wave velocity, the propagation angles and the associated elastic constants can be calculated simultaneously. The calculated angles and the pure transverse mode cross check afforded by the pure transverse mode relations are listed in Tables 4 and 5. Despite small compositional variations, the method of Fisher and McSkimin leads to a maximum difference of only 0.6% in the calculated and measured values of $\rho V^2$ (Table 4). This check justifies the application of this method, even though four different specimens were used.

TABLE 3. Velocities of Pure Modes and Calculated Values of the Adiabatic On-Diagonal Elastic Constants at 25°C

| Elastic Constant | Sample | $\vec{N}$ | $\vec{U}$ | Thickness $d$, mm | Velocity, km/sec | $c_{\mu\mu}{}^S$, Mb | Average $c_{\mu\mu}{}^S$, Mb |
|---|---|---|---|---|---|---|---|
| $c_{11}$ | 3 | [100] | [100] | 6.696 | 8.255 | 2.286 | 2.286 ± 0.001 |
| | 1 | [100] | [100] | 6.794 | 8.253 | 2.285 | |
| $c_{22}$ | 4 | [010] | [010] | 7.176 | 6.915 | 1.604 | 1.605 ± 0.001 |
| | 1 | [010] | [010] | 7.664 | 6.920 | 1.606 | |
| $c_{33}$ | 1 | [001] | [001] | 6.783 | 7.920 | 2.104 | 2.104 ± 0.001* |
| $c_{44}$ | 1 | [010] | [001] | 7.664 | 4.934 | 0.8167 | 0.8175 ± 0.0009 |
| | 4 | [010] | [001] | 7.176 | 4.940 | 0.8184 | |
| | 1 | [001] | [010] | 7.683 | 4.936 | 0.8174 | |
| $c_{55}$ | 1 | [100] | [001] | 6.794 | 4.745 | 0.7553 | 0.7548 ± 0.0007 |
| | 3 | [100] | [001] | 6.696 | 4.744 | 0.7551 | |
| | 1 | [001] | [100] | 7.683 | 4.741 | 0.7541 | |
| $c_{66}$ | 1 | [100] | [010] | 6.794 | 4.814 | 0.7772 | 0.7766 ± 0.0005 |
| | 3 | [100] | [010] | 6.696 | 4.809 | 0.7759 | |
| | 1 | [010] | [100] | 7.664 | 4.810 | 0.7763 | |
| | 4 | [010] | [100] | 7.196 | 4.813 | 0.7768 | |

*Error assumed to be equal to that of $c_{11}$ and $c_{22}$.