TABLE II. Velocities and elastic constants derived from Eqs. (1), (2), and (4).

Computation equation used	Velocities along $[1\bar{1}0]$ ($\times 10^5$ cm sec^{-1}) v_L	v_{T_1}	v_{T_2}	Elastic constants ($\times 10^{12}$ dyn cm^{-2}) c_{11}	c_{12}	c_{44}	Anisotropy ($\times 10^{12}$ dyn cm^{-2}) $c=c_{11}-c_{12}-2c_{44}$
(4)	8.99	6.33	5.84	3.62	0.31	1.99	-0.68
(1)	9.219	6.419	5.921	3.881	0.429	2.029	-0.606
(2)	9.230	6.425	5.927	3.891	0.433	2.032	-0.606

N is Avogadro's number, M is the molecular weight, ρ is the density, q is the number of atoms per molecule, v_m is the averaged acoustic velocity.

The averaged acoustic velocity can be calculated from the expression

$$v_m=\left(\tfrac{1}{3}\left[2/V_T^3+1/V_L^3\right]\right)^{-\frac{1}{3}}, \tag{15}$$

where V_L and V_T are, respectively, the averages of the compressional and shear acoustic velocities along the [100], [110], and [111] directions given above in Eqs. (6)–(12).

7. MEASUREMENTS

Velocity measurements by the coherent pulse/cw technique were made on a single crystal of TiC. Two suitable $[1\bar{1}0]$ surfaces were ground and polished flat to $\lambda/4$ of sodium light and parallel to within 0.5′. The distance ℓ_S between these two polished faces was 0.7836 cm. A [110] orientation was chosen as the three independent velocities in this direction can be used in Eqs. (8), (9), and (10) and are adequate for calculating all three elastic constants c_{11}, c_{12}, and c_{44}, from which the velocities along the [100] and [111] directions may be computed. The velocities in all three directions are required for estimating v_m of Eq. (15). An X-cut quartz transducer, bonded to the sample by means of Canada balsam, was used to determine the compressional velocity. An AC-cut quartz transducer, bonded to the sample with Salol, was used for measuring both shear velocities, by first orienting the transducer polarization along the [110] and then the [001] direction. The pertinent parameters used in the computation of v_L, v_{T_1}, and v_{T_2} are given in Table I and Appendix I. The tabulated values of ν_n and $\Delta\nu_{av}$ are direct measurements recorded by the electronic counter, while n was calculated using Eq. (3). The data of Table I were used to calculate the velocities according to Eqs. (4), (1), and (2) and are listed in Table II. These values were then used to compute the elastic constants from Eqs. (8), (9), and (10). Table II lists these values together with values of the anisotropy c, computed from the definition of c for Eq. (5). The compressional and shear velocities in the [100] and [111] directions listed in Table III were calculated from Eqs. (6), (7), (11), and (12) using the elastic constants listed in Table II. The average velocities V_L and V_T were obtained from the velocities of Table III and used in Eq. (15) for obtaining the mean velocity v_m. This value of velocity was used to calculate the Debye temperature θ according to Eq. (14). The numerical values of the remaining parameters of Eq. (14) are listed in Appendix I. The velocities derived from Eqs. (1) and (2) are correct to within 10^{-3}, whereas the

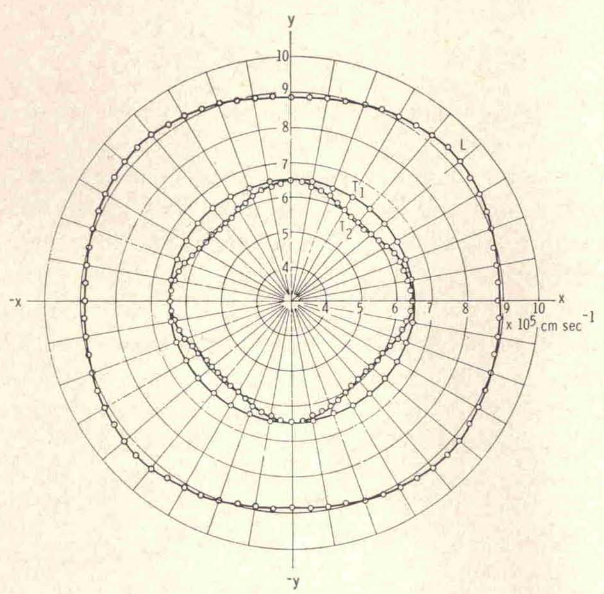

FIG. 8. Curves of intersection in (x-y) plane of velocity surface of TiC.

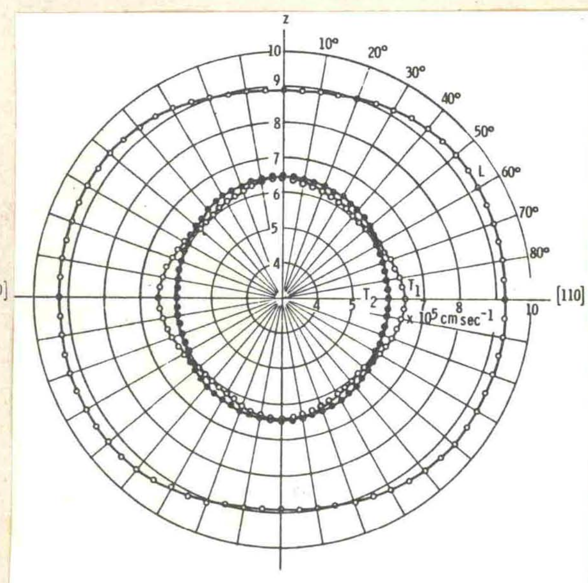

Fig. 9—Curves of intersection in (110) plane of velocity surface (TiC)

TABLE III. Velocities and Debye temperatures derived from Eqs. (1), (2), and (4).

Computation equation used	Measured velocities [1$\bar{1}$0] ($\times 10^5$ cm sec^{-1}) v_L	v_{T_1}	v_{T_2}	Calculated velocities [100] ($\times 10^5$ cm sec^{-1}) v_L	$v_{T_1}=v_{T_2}$	Calculated velocities [111] ($\times 10^5$ cm sec^{-1}) v_L	$v_{T_1}=v_{T_2}$	Mean velocity ($\times 10^5$ cm sec^{-1}) v_m	Debye θ °K
(4)	8.99	6.33	5.84	8.55	6.37	9.10	6.01	6.69	920
(1)	9.219	6.419	5.921	8.878	6.419	9.330	6.092	6.787	934
(2)	9.230	6.425	5.927	8.890	6.424	9.369	6.096	6.795	935

value of v_L derived from Eq. (4) is less than the true value by 2.5% and those of v_{T_1} and v_{T_2} by 1.5% as the end effect of the transducer is neglected in this equation. These values have been included to indicate the magnitudes of the errors introduced in the derived values of velocities, elastic constants and Debye temperature by neglecting the end effect of the transducer (see also Appendix II). The semi-angle of the cone of refraction of shear waves along the [111] direction is 4.5° according to Eq. (13). A more exact value of the mean velocity v_m of Eq. (15) can be derived from Figs. 8 and 9 as shown in Appendix II. This leads to a value of Debye temperature slightly lower than that given in Table III. However, these values are within 0.3% of each other. Thus the method used to determine the values of v_m given in Table III is justified for slightly anisotropic materials.

8. DISCUSSION

The coherent pulse/cw technique is a convenient, quick and fairly accurate method of determining the velocities, elastic constants, and Debye temperature of solids. By the use of an exponential waveform generator[5,10] the ultrasonic attenuation of the sample can be measured at the time the velocity measurements are being made. This method, while retaining the advantages of both pulse and cw techniques, avoids some of the disadvantages of each. The linearity of the CRO time base and the need for an accurate delay generator, which increase the complexity of the electronic instrumentation required for velocity measurement by conventional pulse echo techniques, as well as uncertainty in transit time measurement due to the presence of the transducer[11] are avoided in the coherent pulse/cw technique. The use of a wide band receiver and a variable attenuator in the latter technique, facilitates the rapid and accurate determination of mechanical resonance frequencies not possible with conventional cw systems even in the hands of a skilled operator.

[10] J. de Klerk, Ultrasonics 2, 137 (1964).
[11] E. W. Kammer, Report of NRL Progress, January 1965.

9. ACKNOWLEDGMENTS

The gated amplifier of Fig. 6 was designed by M. Menes and used by M. Menes and D. I. Bolef in their original work on the acoustic nuclear magnetic resonance technique.[3] The author would like to thank R. C. Kuzincki for orienting and F. N. Hauber for polishing the TiC crystal, and Miss Brenda J. Kagle for setting up the computer program used to obtain the data plotted in Fig. 9.

APPENDIX I

Density of quartz, $\rho_T = 2.648$ g cm^{-3}

Density of TiC, $\rho_S = 4.922$ g cm^{-3}

Length of sample, $\ell_S = 0.7836$ cm

Ratio $m_{T_x}/m_S = 0.0249$

Ratio $m_{T_{ac}}/m_S = 0.0142$

$$h = 6.6251\times10^{-27} \text{ erg sec}$$

$$k = 1.3805\times10^{-16} \text{ erg deg}^{-1}$$

$$N = 6.0248\times10^{23} \text{ (g mole)}^{-1}$$

$$q = 2$$

$$M = 59.91$$

APPENDIX II

Equation (5) has been used to derive the curves of intersection of the velocity surface of TiC in the [x-y] and [110] planes, by substitution of the measured values of c_{11}, c_{12}, and c_{44} and appropriate values of direction cosines ℓ, m, n in this equation. The results of this computation are given in Figs. 8 and 9, which indicate that the material is fairly isotropic, and hence the approximate method used in Sec. 7 for obtaining the mean velocity v_m is justified. A more exact determination of v_m based on the data presented in Figs. 8 and 9 is 6.756×10^5 cm sec^{-1}, which leads to a value of 930°K for the Debye temperature.