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THE ELASTIC CONSTANTS OF Fe-Ni-C ALLOYS

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The elastic constants of Fe-Ni-C alloys

by

Daniel Eugene Diesburg

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The elastic constants of Fe-Ni-C alloys*

Daniel Eugene Diesburg

ABSTRACT

The adiabatic elastic constants of a series of Fe-Ni-C alloy single crystals have been measured in the temperature range $M_s \overset{\sim}{+} 10^{\circ}C$ to room temperature. Certain criteria have been observed relating elastic constant temperature dependence to martensite morphology. If $dC^L/dT < 0$, $dC'/dT < 0$, and $dC_{44}/dT < 0$, "2,2,5" martensite will nucleate and grow. If $dC^L/dT > 0$, either "2,5,9" or "1,1,1" martensite will be present in the transformed alloy. The temperature dependence of either shear constant does not effect the "2,5,9" mechanism. However, if $dC_{44}/dT < 0$ and the alloy contains no carbon, "1,1,1" martensite will nucleate and grow below room temperature instead of "2,5,9" martensite. It has been observed that both "2,2,5" and "2,5,9" martensite can be present in the same alloy if $dC^L/dT \simeq 0$ and if $dC'/dT < 0$. It is

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believed that the growth of either type of martensite can nucleate the other type under these conditions.

The compositional dependence of elastic constants has been used to estimate the values of the elastic constants for the face-centered cubic allotrope of pure iron at room temperature. The elastic constants of paramagnetic iron based on extrapolation are $C_{11} = 2.760 \times 10^{12}$ dynes/cm^2, $C_{12} = 1.735 \times 10^{12}$ dynes/cm^2 and $C_{44} = 1.363 \times 10^{12}$ dynes/cm^2. These values give face-centered cubic iron a Debye temperature of 484.4°K.

INTRODUCTION

The martensite transformation in ferrous alloys because of its importance to industrial applications has long been the subject of intense investigation. It has become apparent that the word "martensite," as it is used to describe the displacive, shear-like transformation which occurs in ferrous alloys upon cooling, is a gross oversimplification. Not only is the transformation itself complex, but it forms three different habit plane[1] relationships depending on alloy content and/or temperature of transformation. A mechanism of transformation which can explain the observed martensite morphology in all ferrous alloys is the ideal goal. Any investigation which contributes to the attainment of that goal will probably be judged as significant.

All phase transformations including martensitic transformations involve two distinct stages: nucleation and growth. The first not only must be concerned with the conditions under which the nucleus forms but also the actual mechanism of nucleation. Martensite transformations are known to be heterogeneously nucleated and are specifically

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[1] The habit plane is defined as the plane of intersection between the parent and product phase.

believed to be nucleated by a dislocation mechanism. The relationship between the nuclei and the final martensite morphology is not known. Thermodynamic considerations based on the assumption that the nuclei have the shape of lenticular plates have had very limited success. The shape of the nucleus may or may not be the same as that of the full-grown plate. The mechanical properties of the parent phase may support one mechanism of nucleation. The same properties, coupled with those of the product phase, may allow a completely different growth mechanism leading to the final morphology of the martensite plates. No matter what the mechanisms, it should be fairly obvious that the mechanical properties of the parent austenite phase influence both the nucleation and growth processes.

Recent work (1) supports the idea that the resistance to plastic deformation of the austenite controls the type of martensite which will nucleate and grow. This is consistent with the idea that the habit plane is the one involving the minimum plastic work in the transformation (2). The nucleation mechanism may or may not be the same for each type of martensite but the growth mechanism surely must be different in each case. Before the final nucleation and growth mechanisms are postulated the elastic properties of the parent austenite phase must be known.

The energy associated with a constrained transformation has been generalized for a homogeneous, isotropic, elastic medium by Eshelby (3-5). When his theory was applied to the nucleation of the martensite transformation (6), it was shown that the elastic strain energy was directly proportional to the shear modulus of the parent phase. This elastic model was further expanded (7) to adopt the Frank (8) dislocation model of the austenite-martensite interface. The strain energy was again proportional to the shear modulus. Fisher (9) assumed that the interfacial energy was comprised mainly of the core energy of the interfacial screw dislocations. Again the interfacial energy was found to be proportional to the shear modulus. Since the elastic properties of the austenite seem to be important in determining the restraints on the martensite transformation, it is reasonable to hypothesize that the different types of martensite result from variations in the shear modulus of the parent phase. The Young's modulus and the shear modulus have been measured (10) for polycrystalline ferrous alloys as the M_s was approached but no definite conclusion could be made concerning the effect these values had on the martensite morphology.

It has long been known that the elastic properties of a crystalline solid can be used to speculate on the bonding characteristics of its lattice. Zener (11) originally pointed out that the elastic constants could be used to predict lattice stability, or instability, by observing the value of the shear constants, particularly $\frac{1}{2}(C_{11}-C_{12})$. A lattice with a small value of $\frac{1}{2}(C_{11}-C_{12})$ or a high value of the elastic anisotropy, $2C_{44}/(C_{11}-C_{12})$, should tend to be unstable and undergo a phase transformation. This prediction was verified for certain body-centered cubic (12-15), face-centered cubic (16-20), and also for hexagonal close-packed metals (21). However, measurements made on an iron-nickel alloy (22) indicated only a small increase in elastic anisotropy as the M_s[1] was approached. This would seem to indicate that high anisotropy establishes a sufficient but not a necessary condition for lattice instability.

The elastic constants of the parent austenite phase are valuable in themselves. In the event a nucleation and growth mechanism is ever postulated; the anisotropic properties, or

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[1] M_s is defined as the temperature at which martensite begins to form upon cooling.

more appropriately, the elastic constants of the parent phase would have to be known. It would also probably be necessary to know the elastic constants of the product and any intermediate phase before a complete mechanism could be confirmed.

Purpose of Investigation

In light of the above it seems logical that the single crystalline elastic constants of a ferrous alloy would have some useful information about the martensite transformation. It has been pointed out that the nature of the parent phase, austenite, should have a definite effect on the morphology of the product phase, martensite.

The purpose of this investigation was to measure the elastic constants of a series of iron-rich, face-centered cubic alloy single crystals over the temperature range $M_s \overset{\sim}{+} 10^{\circ}C$ to room temperature. The alloy system selected was one wherein all three types of martensite were known to occur. It was hoped that a comparison of the morphology would reveal some consistent relationship. Following the original plan of the experiment, a large number of single crystals were prepared whose composition range permitted an extrapolation of the elastic constants to those of pure, face-centered cubic iron. In this way it was hoped that at least the room temperature elastic constants of face-centered cubic iron could be approximated.

Nickel and carbon both stabilize austenite at room temperature; therefore, a series of Fe-Ni-C single crystals was used for this investigation. In addition to allowing all three types of martensite to nucleate and grow, this alloy system also supports a paramagnetic to ferromagnetic transition as the nickel content is increased. The change in the elastic constants, if any, as these boundaries are crossed would be very interesting to analyze.

Crystal Elasticity

A generalized form of Hooke's Law may be written

$$\sigma_{ij} = C_{ijk\ell}\, e_{k\ell} \qquad (1)$$

where σ_{ij} and $e_{k\ell}$ are homogeneous stresses and homogeneous strains respectively and are specified by second-rank tensors. The linear constants of proportionality which relate stress to strain in the elastic limit are called the elastic constants and are specified by the fourth-rank tensor

$$C_{ijk\ell} = \frac{d\sigma_{ij}}{de_{k\ell}} \; . \qquad (2)$$

There are 81 such constants but $C_{ijk\ell}$ cannot be distinguished from $C_{ij\ell k}$ or $C_{jik\ell}$. Therefore, the set of 81 reduces to 36, and for convenience the tensor notation can be changed to matrix notation (23) with the following result:

$$\sigma_i = C_{ij}\ e_j . \tag{3}$$

For an adiabatic process the First Law of Thermodynamics can be written

$$dE = dW \tag{4}$$

where dE is the internal energy and dW is the amount of work done on the system. The work done when a single crystal is subjected to a small homogeneous strain can also be written as

$$dW = \sigma_i\ de_i . \tag{5}$$

If Hooke's Law is obeyed this can be written as

$$dE = dW = C_{ij}\ e_j\ de_i . \tag{6}$$

Therefore, C_{ij} is further defined as

$$C_{ij} = \frac{d}{de_j}\left(\frac{dE}{de_i}\right). \tag{7}$$

Since dE is a state property,

$$C_{ij} = C_{ji} . \tag{8}$$

Equation 8 reduces the set of 36 elastic constants to 21. The symmetry constraints of various crystal classes further reduces the number of independent constants. As shown by Nye (23), there are only three independent elastic constants for cubic crystals: C_{11}, C_{12}, and C_{44}.

It is possible to determine C_{11}, C_{12}, and C_{44} by measuring the velocity of an acoustic wave propagated in specific crystallographic directions. As shown by Kittel (24), all three independent elastic constants for a cubic crystal can be obtained by measuring the velocity of appropriate modes of vibration in the [110] direction from the following relationships:

$$C = C_{44} = \rho v_t^2 \qquad (9)$$

$$C' = \tfrac{1}{2}(C_{11} - C_{12}) \ \rho v_t'^2 \qquad (10)$$

$$C^L = \tfrac{1}{2}(C_{11} + C_{12} + 2C_{44}) = \rho v_L^2 \qquad (11)$$

where v_t is the velocity of a transverse or shear wave polarized in the [001] direction; v_t' is the velocity of a shear wave polarized in the $[1\bar{1}0]$ direction; and v_L is the velocity of a longitudinal wave in the [110] direction. ρ is the density of the crystal.

The determination of elastic constants by sonic measurements is described by Huntington (25) as a dynamic determination. These usually give the adiabatic elastic constants because thermal currents within the specimen cannot maintain constant temperature for the available frequency range and direct contact with the surroundings is generally insufficient for isothermal conditions. The difference between adiabatic and isothermal elastic constants is usually about 1% (26).

EXPERIMENTAL PROCEDURE

Sample Preparation

Twenty-eight single crystals of face-centered cubic Fe-Ni-C alloys were prepared for this investigation. The compositions ranged from 11.3 to 33.3 a/o Ni and from 0 to 4.52 a/o C. The analyses of the charge constituents are given below.

Table 1. Analysis of charge constituents

Iron	Nickel	Carbon
Fe-99.94 w/o	Ni-99.8 w/o	spectrographically
C-30 ppm	Pb-.001 w/o	pure carbon
N-50 ppm	Co-.005 w/o	rod
O-150 ppm	Fe-.010 w/o	

Single crystals were grown by a modified Bridgeman technique (27). The appropriately weighed constituents were first arc melted into buttons under a ~ 2μ vacuum to aid in homogenizing the alloys. The buttons were then sectioned on a cutoff wheel and loaded into cone-tipped, tapered Al_2O_3 crucibles for growth into single crystals. The alloys were held in a molten condition under a vacuum in the Bridgeman for at least two hours to allow further homogenization and to "boil" away any gaseous material which might be in the alloy.

The atmosphere around the alloy during growth was either a $\sim 2\mu$ vacuum or a vacuum which had been back-filled with helium. A growth rate of 9.0×10^{-5} cm/sec was used for all alloys. The final crystals were approximately 2 cm in diameter, 5 cm in length, and weighed about 120 gm.

Single crystals grown by the Bridgeman technique were known to have composition gradients similar to that shown in Figure 1, depending on the amount of mixing occurring in the melt as the crystal solidified. If the molten alloy undergoes no mixing , the composition of the crystal between sections I and II would be C_0. A microprobe scan along the crystal axis on two alloys revealed $\Delta C > 0$. It was impossible to predict the exact shape of the concentration gradient because the diffusion coefficients of the ternary constituents and the ternary phase diagram were not known. The microprobe revealed no radial concentration gradients or microsegregation.

The extremities of the single crystals were sectioned along lines I and II to remove the growth transients and to allow visual examination for extraneous grains by polishing and etching the cut surfaces. If the ingot was a single crystal or very large grained, the alloy was sealed in quartz

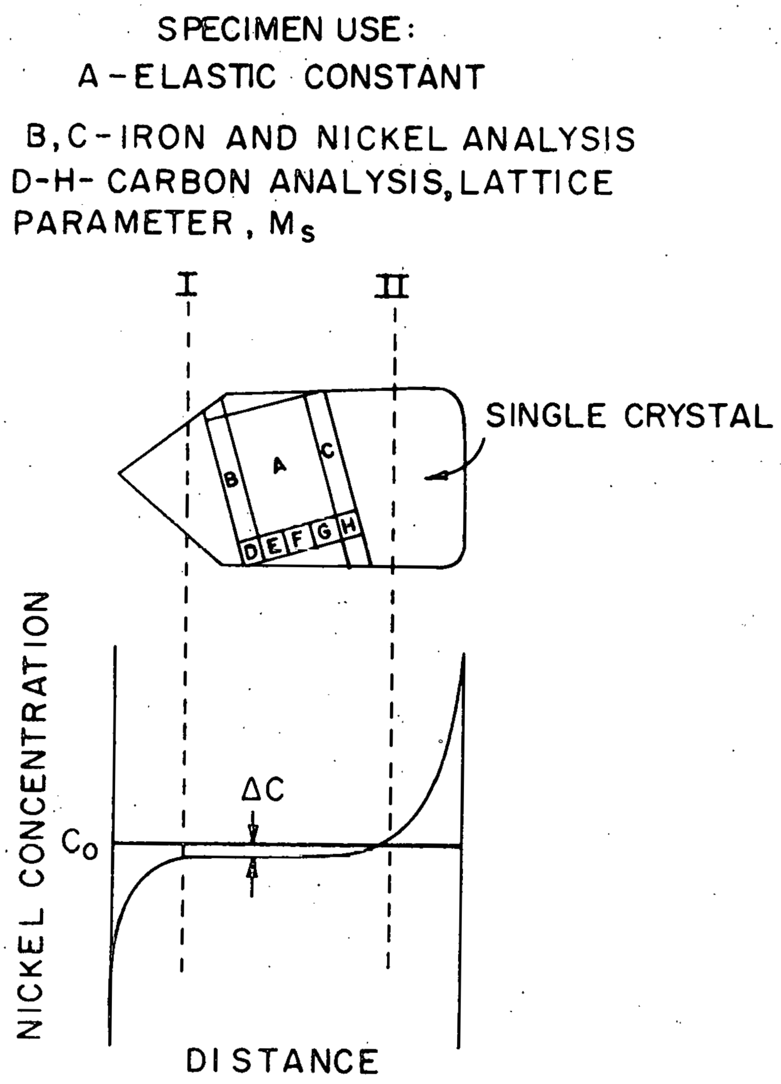

Figure 1. Schematic of nickel gradient present when the molten metal is not completely mixed during solidification. Note the typical locations of various specimens

under a 2μ vacuum and homogenized at 1200°C for at least 120 hours. This final homogenization treatment was performed in a non-inductively wound resistance tube furnace coupled to a 1μ capacity vacuum system. To avoid any possibility of a diffusion controlled face-centered cubic to body-centered cubic transformation, which does occur in the Fe-Ni system during a slow cool, each crystal was pushed from the hot zone of the furnace and into a chamber whose walls were cooled by circulating water. X-ray analysis of the final crystal never revealed the presence of any diffusion controlled second phase.

Not all 28 single crystals could receive the 120 hour homogenization treatment. Six of the compositions had martensite present at room temperature in the otherwise single crystals. Such crystals would become polycrystalline if heated above the austenite start temperature because the martensite transformation was not reversible. These six crystals were otherwise treated in the same manner as the other 22 crystals. Microprobe analysis had shown that the iron, nickel, and carbon concentration gradients were small even before the final homogenization treatment, although the detection of carbon by a microprobe is questionable. If great care was taken when choosing the location from which to cut the elastic constant specimen, the concentration gradients were kept to a minimum even without the 120 hour anneal.

Figure 1 also indicates typical locations of specimens used for elastic constant, lattice parameter, M_s, and chemical analysis determination. All sectioning was performed by electromachining on a Sparkatron spark cutter. An average chemical analysis was used in all elastic constant results; whereas, the analysis used for M_s and lattice parameter results was obtained from material located nearest these specimens. Oftentimes, carbon analysis was obtained directly from the M_s or lattice parameter specimens. All chemical analyses (Table 2) were performed by the Ames Laboratory Analytical Services Group of the U.S.A.E.C., Ames, Iowa. Iron and nickel analyses were checked by two different wet chemical methods on two specimens with very consistent results.

Elastic constant specimens were cut to expose at least one pair of parallel (110) faces. The faces were polished to parallelism ($\pm$ 0.0003 cm) on No. 600 grit paper and the distance between faces was measured by micrometer. Sometimes another pair of (110) and (100) faces were exposed and polished parallel. The distances between (110) faces varied

Table 2. Crystal compositions, thickness, lattice parameter and theoretical densities

Crystal No.	a/o Ni ± 0.1	a/o C	Thickness (cm) ± .0002	a_o (A) ±.0003	ρ gm/cm^3
1	33.3	0.00	0.845	3.5850	8.1879
2	29.0	0.00	0.724	3.5820	8.1903
3	28.8	0.56±.05	0.780	3.5857	8.1749
4	27.9	1.21±.05	1.356	3.5910	8.1513
5	28.5	2.50±.05	0.964	3.5963	8.1369
6	27.9	3.22±.10	0.900	3.5997	8.1258
7[a]	27.9	4.00±.20	0.836	3.5996[b]	8.1262
8[c]	27.2	0.00	0.781	3.5803	8.1950
9	26.4	0.94±.05	0.754	3.5854	8.1744
10	26.9	1.21±.10	0.924	3.5882	8.1633
11	26.3	2.36±.09	0.785	3.5951	8.1361
12	26.1	2.95±.10	1.099	3.5977	8.1283
13	23.9	1.49±.08	0.930	3.5875	8.1592
14	23.9	2.49±.08	0.809	3.5935	8.1366
15	22.9	2.99±.07	1.353	3.5969	8.1227
16[a]	23.2	4.00±.20	0.750	3.5965[b]	8.1096
17[c]	21.3	1.76±.20	0.828	3.5859	8.1569
18	21.2	2.53±.04	0.758	3.5945	8.1192
19	21.1	3.21±.08	0.870	3.5987	8.1079
20[a]	21.0	4.36±.20	0.675	3.6022[b]	8.0995
21	19.0	2.89±.08	0.916	3.5963	8.1043
22	18.7	3.10±.03	0.921	3.5980	8.0957
23	18.6	3.80±.03	0.699	3.5999	8.0946
24[a]	15.9	4.35±.20	0.935	3.6022[b]	8.0748
25[c]	13.9	4.06±.02	0.710	3.6016	8.0680
26[c]	13.9	4.17±.15	0.928	3.6007	8.0761
27[a]	13.8	4.52±.15	0.727	3.6030[b]	8.0703
28[c]	11.3	4.29±.15	0.998	3.6030	8.0578

[a] Graphitized.

[b] Lattice parameters obtained by interpolation.

[c] Martensite present at 298°K.

from 0.675 to 1.356 cm and the final specimens weighed from 5 to 30 gm.

Back reflection Laue techniques were used to orient the bulk crystals on a two-circle goniometer to within ± 0.5 degrees from the desired face. The goniometer and crystal were aligned on the Sparkatron by eye and the faces exposed. The faces were rechecked for correct orientation after polishing and etching. A 1:1 solution of concentrated HCl and HNO_3 was used as an etchant to reveal the presence of any extraneous grains in the final specimens.

M_s Determination

Since the elastic constants were to be measured between room temperature and a temperature $M_s \tilde{+} 10^{\circ}C$ of each alloy, it was necessary to know the M_s. Specimens with a ~4 mm^2 cross-sectional area and from 1 to 2 cm in length were cut from each single crystal. The M_s was measured for each alloy (28) by recording the voltage drop across the specimen as the temperature was lowered. Table 3 gives the M_s of each alloy in both the "as polished" and the stress relieved condition.

Table 3. Average martensite start temperatures of Fe-Ni-C alloys

Crystal	Single crystal M_s (^oC) "as polished"	Single crystal M_s (^oC) "stress relieved"
1[a]		
2	-3	0
3	-34	-47
4	-68	-76
5	-90	-112
6[b]		
7[b]		
8[c]		
9	-24	-36
10	-34	-47
11	-75	-78
12	-103	-110
13	-10	-25
14	-48	-48
15	-66	-69
16[b]		
17[c]		
18	-27	-35
19	-54	-63
20[a]		
21	-26	-39
22	-28	-32
23	-56	-60
24[a]		
25[c]		
26[c]		
27[c]		
28[c]		

[a] Not measured.

[b] Below liquid nitrogen temperature.

[c] Above room temperature.

Density Determination

Lattice parameters of the Fe-Ni-C alloys have been determined (29) from specimens cut from the single crystals used in this investigation and are given in Table 2 and plotted in Figure 2. Theoretical densities were calculated by assuming that the iron and nickel atoms occupy 100% of the lattice sites. The weight contributed by the interstitial carbon atoms was simply added to the weight contributed by the iron and nickel atoms. The density results are given in Table 2. Hydrostatic density determinations were also performed on the elastic constant specimens for comparison (Appendix A), but were never used in the present investigation.

Acoustic Measurements

Ultrasonic transit times were measured by two different methods: 1) the pulse-superposition technique as developed by McSkimin (30-32) and 2) the pulse-echo-overlap technique as developed by Papadakis (33) with modifications (34). Only the McSkimin technique was used to measure the temperature dependence of the transit times. Oriented 10 MHz, gold plated quartz transducers were used to introduce the mechanical pulses into the crystals. An X-cut transducer generated the longitudinal pulse in the [110] direction and a Y-cut trans-

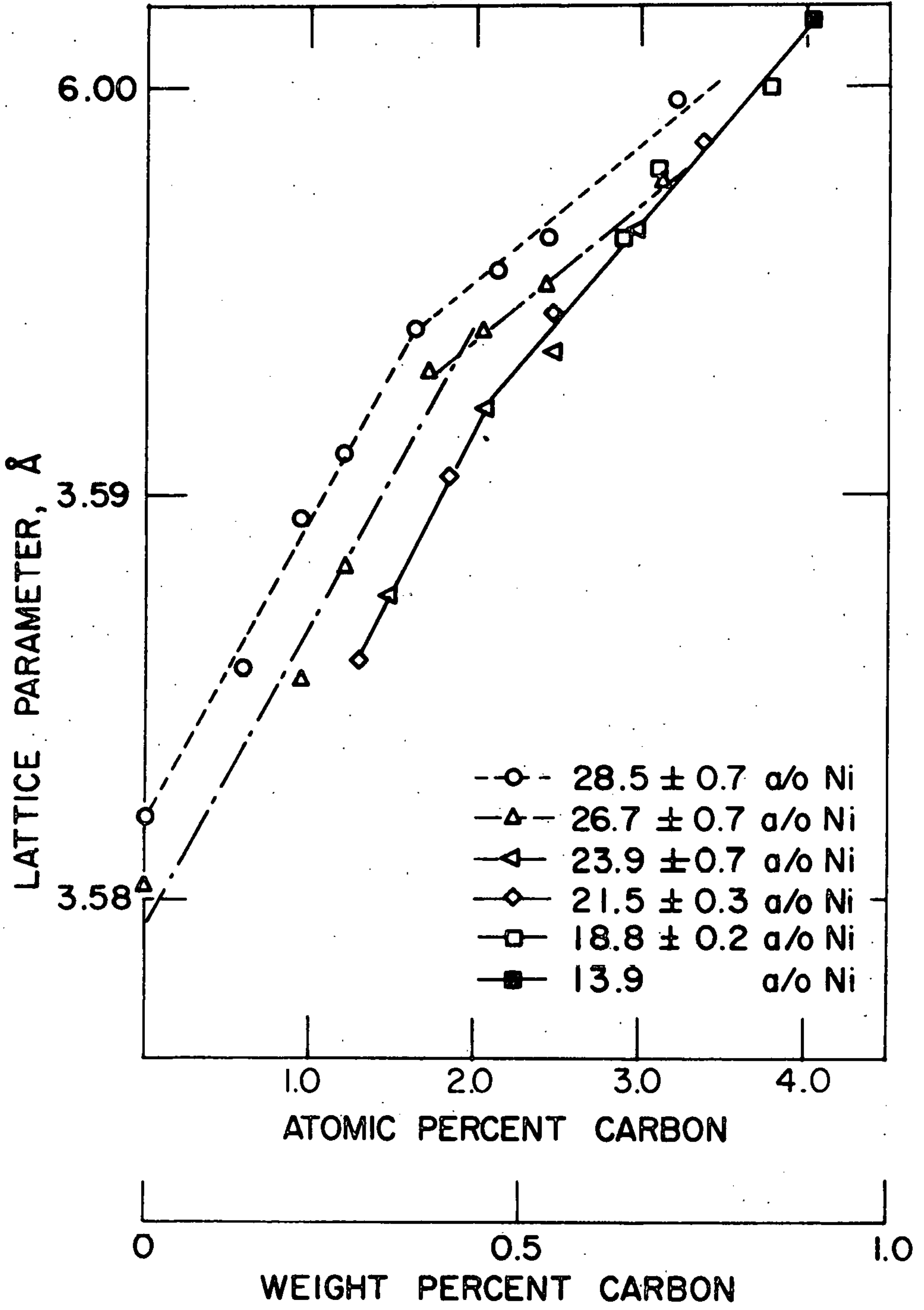

Figure 2. Lattice parameters of Fe-Ni-C alloys

ducer generated the shear pulses, (110)$[1\bar{1}0]$ and (110)[001]. Phenyl salicylate (Salol) was used to bond the transducers to the crystal at room temperature and lower until the bond was broken which usually occurred at -5 or -10°C. Nonaq stopcock grease was used for the bond below the limit of Salol.

Continuous cooling at a rate of about 1°C/min. was provided by placing the specimen in a copper container which was wrapped with resistance heating wire. The copper container and specimen were then placed over a dewar containing liquid nitrogen. The distance above the liquid nitrogen and the heating current were adjusted to give the desired cooling rate. A thermocouple taped in contact with the specimen was used to record the temperature. The transit times were measured in 5°C intervals. The specimens were usually cooled to within 10 or 20°C of the measured M_s for each alloy.

EXPERIMENTAL RESULTS

The adiabatic elastic constants C^L, C', and C_{44} were calculated from the transit velocities using Equations 9 to 11. From these, the three independent elastic constants C_{11}, C_{12}, and C_{44} were determined and are listed in Table 4 along with C^L and C'. The temperature dependence ($\pm$ 0.5°C) of these values was determined by the pulse-superposition technique. At room temperature the pulse-echo-overlap technique was used to verify these measurements. Although the random error involved in each technique was within 0.2% the difference between the values obtained by each technique was sometimes as high as 1.0%. Usually the superposition technique transit time was higher than the pulse-echo value. Oftentimes the pulse-superposition technique would leave doubt as to which resonant frequency gave the correct transit time. Since the pulse-echo technique left no doubt as to the correct value of the transit time, these values were used instead of the pulse-superposition values. The temperature dependence of the transit times, as measured by the pulse-superposition technique, was assumed to have the correct temperature slope but the values were adjusted to agree with the room temperature values obtained by the pulse-echo technique.

Table 4. The adiabatic elastic constants of Fe-Ni-C alloys in units of 10^{12} dyne/cm^2

Crystal	Temp. (^oK)	C^L	C'	C_{44}	C_{11}	C_{12}
1	298	2.1540	0.2379	1.0591	1.3328	0.8570
	293	2.1506	0.2366	1.0586	1.3286	0.8554
	288	2.1489	0.2348	1.0581	1.3256	0.8591
	283	2.1452	0.2336	1.0574	1.3215	0.8542
	278	2.1430	0.2323	1.0567	1.3186	0.8540
	273	2.1409	0.2306	1.0562	1.3154	0.8540
2	298	2.3521	0.3050	1.1313	1.5258	0.9157
	293	2.3440	0.3048	1.1323	1.5166	0.9061
	288	2.3355	0.3046	1.1331	1.5070	0.8978
	283	2.3268	0.3043	1.1339	1.4972	0.8886
	278	2.3188	0.3092	1.1346	1.4881	0.8802
	273	2.3122	0.3036	1.1354	1.4804	0.8731
3	298	2.3672	0.3026	1.1262	1.5433	0.9387
	293	2.3622	0.3019	1.1271	1.5370	0.9331
	288	2.3533	0.3016	1.1282	1.5268	0.9235
	283	2.3430	0.3014	1.1290	1.5154	0.9126
	278	2.3332	0.3010	1.1292	1.5050	0.9029
	273	2.3221	0.3008	1.1300	1.4929	0.8913
	268	2.3135	0.3004	1.1307	1.4832	0.8824
	263	2.3080	0.2998	1.1314	1.4764	0.8768
	258	2.3020	0.2994	1.1324	1.4671	0.8692
	253	2.2980	0.2990	1.1336	1.4634	0.8654
4	298	2.2887	0.2984	1.1076	1.4795	0.8829
	293	2.2808	0.2978	1.1078	1.4709	0.8752
	288	2.2726	0.2972	1.1083	1.4615	0.8672
	283	2.2653	0.2966	1.1084	1.4535	0.8604
	278	2.2586	0.2961	1.1087	1.4460	0.8538
	273	2.2521	0.2956	1.1089	1.4388	0.8475
	268	2.2455	0.2950	1.1093	1.4311	0.8412
	263	2.2388	0.2944	1.1099	1.4233	0.8345
	258	2.2332	0.2936	1.1106	1.4162	0.8290
	253	2.2241	0.2929	1.1112	1.4058	0.8199
	248	2.2192	0.2923	1.1116	1.3999	0.8152
	243	2.2135	0.2915	1.1118	1.3932	0.8102
	238	2.2068	0.2906	1.1121	1.3853	0.8041
	233	2.2011	0.2899	1.1128	1.3781	0.7983
	228	2.1940	0.2890	1.1132	1.3698	0.7918

Table 4. (Continued)

Crystal	Temp. (^oK)	C^L	C'	C_{44}	C_{11}	C_{12}
5	298	2.2046	0.2856	1.0707	1.4196	0.8483
	293	2.1984	0.2854	1.0708	1.4130	0.8423
	288	2.1930	0.2845	1.0707	1.4078	0.8366
	283	2.1877	0.2833	1.0703	1.4008	0.8341
	278	2.1810	0.2822	1.0698	1.3934	0.8299
	273	2.1760	0.2813	1.0694	1.3880	0.8254
	268	2.1694	0.2804	1.0690	1.3808	0.8200
	263	2.1630	0.2793	1.0686	1.3737	0.8150
	258	2.1570	0.2781	1.0675	1.3676	0.8114
	253	2.1524	0.2772	1.0664	1.3632	0.8088
	248	2.1478	0.2761	1.0658	1.3582	0.8059
	243	2.1420	0.2750	1.0650	1.3520	0.8019
	238	2.1380	0.2738	1.0639	1.3480	0.8003
	233	2.1318	0.2727	1.0632	1.3413	0.7959
	228	2.1252	0.2715	1.0631	1.3337	0.7907
	223	2.1186	0.2704	1.0625	1.3265	0.7858
	218	2.1136	0.2692	1.0618	1.3211	0.7826
	213	2.1081	0.2680	1.0614	1.3147	0.7787
	208	2.1024	0.2667	1.0606	1.3085	0.7752
	203	2.0960	0.2654	1.0600	1.3014	0.7705
	198	2.0919	0.2644	1.0591	1.2972	0.7684
6	298	2.1566	0.2773	1.0406	1.3933	0.8387
	293	2.1517	0.2760	1.0405	1.3872	0.8351
	288	2.1451	0.2747	1.0403	1.3795	0.8301
	283	2.1408	0.2731	1.0400	1.3740	0.8278
	278	2.1365	0.2717	1.0396	1.3686	0.8251
	273	2.1308	0.2709	1.0390	1.3628	0.8210
	268	2.1262	0.2696	1.0383	1.3575	0.8183
	263	2.1216	0.2682	1.0380	1.3518	0.8154
	258	2.1171	0.2668	1.0376	1.3462	0.8127
	253	2.1107	0.2660	1.0374	1.3392	0.8073
	248	2.1065	0.2646	1.0373	1.3338	0.8046
	243	2.1015	0.2631	1.0369	1.3277	0.8015
	238	2.0978	0.2618	1.0366	1.3229	0.7993
	233	2.0947	0.2604	1.0366	1.3185	0.7978
	228	2.0903	0.2592	1.0365	1.3131	0.7946
	223	2.0834	0.2576	1.0363	1.3047	0.7894
	218	2.0788	0.2566	1.0360	1.2995	0.7862

Table 4. (Continued)

Crystal	Temp. (^oK)	C^L	C'	C_{44}	C_{11}	C_{12}
6	213	2.0750	0.2553	1.0354	1.2949	0.7843
	208	2.0707	0.2540	1.0349	1.2898	0.7819
	203	2.0666	0.2525	1.0348	1.2843	0.7794
	198	2.0622	0.2506	1.0342	1.2785	0.7737
	193	2.0572	0.2491	1.0338	1.2725	0.7742
	188	2.0524	0.2483	1.0335	1.2671	0.7705
	183	2.0477	0.2463	1.0331	1.2609	0.7682
	178	2.0452	0.2447	1.0328	1.2572	0.7677
	173	2.0406	0.2432	1.0323	1.2515	0.7651
	168	2.0381	0.2420	1.0318	1.2483	0.7642
	163	2.0322	0.2406	1.0313	1.2416	0.7604
	158	2.0302	0.2395	1.0310	1.2387	0.7596
	153	2.0272	0.2380	1.0307	1.2345	0.7584
	148	2.0236	0.2365	1.0304	1.2298	0.7567
	143	2.0214	0.2351	1.0300	1.2264	0.7563
	138	2.0179	0.2337	1.0296	1.2220	0.7547
	133	2.0129	0.2324	1.0294	1.2159	0.7510
	128	2.0087	0.2313	1.0290	1.2111	0.7484
7	298	2.1612	0.2750	1.0308	1.4053	0.8553
	293	2.1584	0.2736	1.0293	1.4027	0.8556
	288	2.1566	0.2722	1.0300	1.3988	0.8544
	283	2.1510	0.2709	1.0291	1.3907	0.8489
	278	2.1481	0.2694	1.0296	1.3839	0.8450
	273	2.1454	0.2682	1.0295	1.3791	0.8427
	268	2.1438	0.2667	1.0288	1.3767	0.8434
	263	2.1409	0.2656	1.0281	1.3714	0.8402
	258	2.1380	0.2638	1.0277	1.3661	0.8385
	253	2.1349	0.2625	1.0273	1.3621	0.8371
	248	2.1274	0.2612	1.0267	1.3538	0.8314
	243	2.1234	0.2596	1.0264	1.3485	0.8294
	238	2.1178	0.2584	1.0264	1.3418	0.8250
	233	2.1142	0.2570	1.0259	1.3373	0.8232
	228	2.1116	0.2557	1.0254	1.3329	0.8215
	223	2.1101	0.2544	1.0254	1.3301	0.8213
	218	2.1050	0.2531	0.0253	1.3238	0.8177
	213	2.0994	0.2520	1.0244	1.3170	0.8130
	208	2.0966	0.2512	1.0243	1.3134	0.8111
	203	2.0924	0.2496	1.0241	1.3078	0.8087

Table 4. (Continued)

Crystal	Temp. (^oK)	C^L	C'	C_{44}	C_{11}	C_{12}
7	198	2.0904	0.2482	1.0236	1.3059	0.8095
	193	2.0890	0.2465	1.0227	1.3048	0.8090
	188	2.0846	0.2452	1.0225	1.2993	0.8088
	183	2.0798	0.2436	1.0224	1.2930	0.8059
	178	2.0769	0.2421	1.0215	1.2885	0.8043
	173	2.0726	0.2403	1.0212	1.2826	0.8020
	168	2.0690	0.2395	1.0211	1.2787	0.7998
	163	2.0675	0.2384	1.0210	1.2766	0.7999
	158	2.0666	0.2369	1.0209	1.2746	0.8007
	153	2.0658	0.2359	1.0206	1.2730	0.8013
	148	2.0649	0.2348	1.0203	1.2714	0.8018
	143	2.0642	0.2337	1.0200	1.2699	0.8024
8	298	2.4427	0.3251	1.1598	1.6080	0.9578
	293	2.4350	0.3254	1.1612	1.5992	0.9484
	288	2.4238	0.3256	1.1625	1.5869	0.9357
9	298	2.4347	0.3251	1.1571	1.6028	0.9527
	293	2.4293	0.3256	1.1590	1.5959	0.9447
	288	2.4229	0.3259	1.1610	1.5878	0.9360
	283	2.4187	0.3267	1.1623	1.5832	0.9297
	278	2.4156	0.3272	1.1645	1.5773	0.9228
	273	2.4102	0.3277	1.1658	1.5721	0.9167
	268	2.4024	0.3280	1.1677	1.5628	0.9067
	263	2.3982	0.3284	1.1691	1.5576	0.9007
10	298	2.3932	0.3223	1.1354	1.5801	0.9354
	293	2.3890	0.3228	1.1368	1.5750	0.9294
	288	2.3848	0.3232	1.1382	1.5698	0.9235
	283	2.3806	0.3237	1.1396	1.5648	0.9173
	278	2.3765	0.3241	1.1410	1.5596	0.9114
	273	2.3723	0.3245	1.1424	1.5544	0.9055
	268	2.3682	0.3247	1.1437	1.5491	0.8997
	263	2.3640	0.3252	1.1451	1.5441	0.8936
	258	2.3599	0.3253	1.1465	1.5386	0.8881
	253	2.3558	0.3257	1.1479	1.5335	0.8820

Table 4. (Continued)

Crystal	Temp. (^oK)	C^L	C'	C_{44}	C_{11}	C_{12}
11	298	2.3392	0.3175	1.1051	1.5516	0.9167
	293	2.3311	0.3173	1.1061	1.5423	0.9076
	288	2.3264	0.3172	1.1066	1.5370	0.9027
	283	2.3235	0.3170	1.1072	1.5334	0.8994
	278	2.3188	0.3168	1.1080	1.5276	0.8941
	273	2.3172	0.3166	1.1088	1.5249	0.8918
	268	2.3159	0.3164	1.1098	1.5225	0.8897
	263	2.3111	0.3161	1.1104	1.5168	0.8847
	258	2.3064	0.3158	1.1110	1.5113	0.8796
	253	2.3037	0.3156	1.1118	1.5074	0.8763
	248	2.2984	0.3127	1.1122	1.5014	0.8709
	243	2.2837	0.3150	1.1130	1.4857	0.8557
	238	2.2734	0.3146	1.1134	1.4746	0.8453
	233	2.2697	0.3143	1.1141	1.4699	0.8413
	228	2.2679	0.3140	1.1149	1.4670	0.8390
	223	2.2641	0.3136	1.1158	1.4619	0.8346
	218	2.2569	0.3135	1.1164	1.4541	0.8269
	213	2.2541	0.3133	1.1168	1.4507	0.8240
	208	2.2500	0.3129	1.1175	1.4454	0.8195
	203	2.2475	0.3127	1.1185	1.4418	0.8164
12	298	2.2966	0.3182	1.0817	1.5331	0.8967
	293	2.2873	0.3180	1.0820	1.5232	0.8873
	288	2.2790	0.3177	1.0834	1.5132	0.8778
	283	2.2755	0.3133	1.0838	1.5091	0.8744
	278	2.2717	0.3169	1.0841	1.5045	0.8707
	273	2.2649	0.3165	1.0842	1.4972	0.8641
	268	2.2582	0.3161	1.0854	1.4890	0.8568
	263	2.2531	0.3156	1.0862	1.4826	0.8513
	258	2.2481	0.3152	1.0848	1.4785	0.8481
	253	2.2412	0.3147	1.0854	1.4705	0.8411
	248	2.2356	0.3143	1.0859	1.4640	0.8354
	243	2.2302	0.3182	1.0874	1.4566	0.8290
	238	2.2242	0.3132	1.0892	1.4482	0.8218
	233	2.2203	0.3126	1.0897	1.4432	0.8180
	228	2.2162	0.3124	1.0903	1.4383	0.8136
	223	2.2109	0.3119	1.0904	1.4324	0.8085
	218	2.2032	0.3118	1.0909	1.4240	0.8003
	213	2.1965	0.3112	1.0910	1.4167	0.7943

Table 4. (Continued)

Crystal	Temp. (°K)	C^L	C'	C_{44}	C_{11}	C_{12}
12	208	2.1909	0.3105	1.0911	1.4108	0.7897
	203	2.1844	0.3101	1.0915	1.4022	0.7821
	198	2.1765	0.3097	1.0919	1.3946	0.7753
	193	2.1724	0.3090	1.0922	1.3892	0.7712
	188	2.1680	0.3083	1.0931	1.3832	0.7667
	183	2.1631	0.3079	1.0932	1.3778	0.7620
	178	2.1570	0.3073	1.0936	1.3707	0.7560
	173	2.1509	0.3067	1.0965	1.3612	0.7476
13	298	2.5999	0.3478	1.1571	1.7905	1.0950
	293	2.6027	0.3524	1.1600	1.7951	1.0903
	288	2.5984	0.3534	1.1622	1.7886	1.0817
	283	2.5970	0.3541	1.1646	1.7865	1.0783
	278	2.5991	0.3546	1.1668	1.7870	1.0777
	273	2.6005	0.3552	1.1706	1.7772	1.0667
	268	2.5999	0.3564	1.1785	1.7802	1.0603
14	298	2.5826	0.3448	1.1309	1.7964	1.1068
	293	2.5814	0.3457	1.1336	1.7935	1.1020
	288	2.5804	0.3466	1.1363	1.7907	1.0975
	283	2.5794	0.3473	1.1381	1.7887	1.0940
	278	2.5786	0.3482	1.1399	1.7868	1.0905
	273	2.5760	0.3491	1.1422	1.7829	1.0847
	268	2.5744	0.3500	1.1443	1.7801	1.0882
	263	2.5726	0.3506	1.1463	1.7770	1.0757
	258	2.5706	0.3514	1.1487	1.7732	1.0705
	253	2.5689	0.3522	1.1506	1.7704	1.0661
	248	2.5681	0.3596	1.1525	1.7686	1.0627
	243	2.5662	0.3538	1.1546	1.7655	1.0579
15	298	2.5152	0.3436	1.1101	1.7487	1.0615
	293	2.5122	0.3444	1.1115	1.7451	1.0562
	288	2.5109	0.3449	1.1132	1.7427	1.0528
	283	2.5085	0.3453	1.1153	1.7385	1.0479
	278	2.5064	0.3460	1.1173	1.7350	1.0430
	273	2.5029	0.3467	1.1196	1.7300	1.0367
	268	2.4998	0.3473	1.1213	1.7258	1.0312
	263	2.4950	0.3481	1.1228	1.7204	1.0241
	258	2.4918	0.3489	1.1247	1.7161	1.0182
	253	2.4887	0.3493	1.1266	1.7114	1.0128

Table 4. (Continued)

Crystal	Temp. (°K)	C^L	C'	C_{44}	C_{11}	C_{12}
15	248	2.4840	0.3498	1.1283	1.7056	1.0059
	243	2.4805	0.3504	1.1302	1.7006	0.9998
	238	2.4767	0.3590	1.1321	1.6956	0.9937
	233	2.4725	0.3514	1.1339	1.6899	0.9872
	228	2.4710	0.3518	1.1357	1.6871	0.9834
	223	2.4680	0.3522	1.1373	1.6829	0.9784
	218	2.4626	0.3526	1.1389	1.6762	0.9711
	213	2.4622	0.3529	1.1407	1.6744	0.9685
	208	2.4570	0.3534	1.1423	1.6681	0.9613
16	298	2.4040	0.3414	1.0905	1.6550	0.9721
	293	2.4006	0.3419	1.0910	1.6515	0.9678
	288	2.3882	0.3422	1.0935	1.6469	0.9565
	283	2.3817	0.3425	1.0948	1.6294	0.9444
	278	2.3741	0.3428	1.0955	1.6213	0.9358
	273	2.3638	0.3430	1.0965	1.6103	0.9243
	268	2.3563	0.3432	1.0970	1.6026	0.9160
	263	2.3491	0.3434	1.0985	1.5940	0.9072
	258	2.3459	0.3435	1.0991	1.5903	0.9032
	253	2.3367	0.3437	1.1002	1.5802	0.8927
	248	2.3332	0.3439	1.1015	1.5756	0.8878
	243	2.3275	0.3439	1.1024	1.5690	0.8812
	238	2.3198	0.3439	1.1036	1.5602	0.8723
	233	2.3175	0.3440	1.1044	1.5572	0.8690
	228	2.3134	0.3442	1.1058	1.5518	0.8634
	223	2.3085	0.3442	1.1066	1.5462	0.8577
	218	2.3008	0.3443	1.1078	1.5372	0.8487
	213	2.2984	0.3443	1.1091	1.5337	0.8450
	208	2.2969	0.3444	1.1094	1.5318	0.8430
	203	2.2921	0.3444	1.1104	1.5261	0.8373
	198	2.2899	0.3445	1.1113	1.5231	0.8342
	193	2.2857	0.3446	1.1122	1.5181	0.8290
	188	2.2846	0.3446	1.1126	1.5166	0.8274
	183	2.2812	0.3447	1.1138	1.5120	0.8227
	178	2.2788	0.3446	1.1150	1.5084	0.8192
	173	2.2767	0.3446	1.1167	1.5046	0.8154
	168	2.2727	0.3446	1.1177	1.4995	0.8104
	163	2.2698	0.3445	1.1183	1.4961	0.8070
	158	2.2671	0.3445	1.1189	1.4926	0.8036
	153	2.2628	0.3445	1.1203	1.4870	0.7980

Table 4. (Continued)

Crystal	Temp. (^{o}K)	C^L	C'	C_{44}	C_{11}	C_{12}
16	148	2.2608	0.3446	1.1214	1.4840	0.7948
	143	2.2570	0.3446	1.1224	1.4792	0.7899
	138	2.2544	0.3446	1.1233	1.4758	0.7865
	133	2.2513	0.3447	1.1239	1.4721	0.7828
	128	2.2495	0.3447	1.1253	1.4688	0.7795
	123	2.2473	0.3447	1.1266	1.4654	0.7760
	118	2.2438	0.3447	1.1274	1.4610	0.7716
17	303	2.7173	0.3574	1.1685	1.9063	1.1915
	298	2.7214	0.3585	1.1708	1.9091	1.1921
	293	2.7250	0.3597	1.1750	1.9096	1.1902
18	298	2.6813	0.3546	1.1535	1.8824	1.1732
	293	2.6827	0.3560	1.1569	1.8818	1.1699
	288	2.6836	0.3745	1.1594	1.8816	1.1667
	283	2.6853	0.3538	1.1618	1.8820	1.1652
	278	2.6874	0.3597	1.1644	1.8827	1.1632
	273	2.6896	0.36099	1.1668	1.8838	1.1618
	268	2.6916	0.3619	1.1707	1.8829	1.1590
	263	2.6935	0.3637	1.1721	1.8851	1.1578
	258	2.6954	0.3644	1.1742	1.8855	1.1568
	253	2.6969	0.3654	1.1766	1.8856	1.1549
	248	2.6992	0.3666	1.1794	1.8863	1.1532
19	298	2.6371	0.3560	1.1256	1.8675	1.1555
	293	2.6383	0.3573	1.1284	1.8672	1.1527
	288	2.6402	0.3585	1.1309	1.8677	1.1508
	283	2.6410	0.3597	1.1336	1.8672	1.1477
	278	2.6427	0.3608	1.1359	1.8675	1.1459
	273	2.6437	0.3619	1.1383	1.8673	1.1436
	268	2.6444	0.3629	1.1414	1.8669	1.1440
	263	2.6452	0.3641	1.1427	1.8666	1.1384
	258	2.6463	0.3653	1.1453	1.8662	1.1357
	253	2.6475	0.3664	1.1475	1.8664	1.1336
	248	2.6483	0.3674	1.1503	1.8654	1.1306
	243	2.6491	0.3686	1.1525	1.8652	1.1281

Table 4. (Continued)

Crystal	Temp. (°K)	C^L	C'	C_{44}	C_{11}	C_{12}
20	298	2.5864	0.3518	1.0954	1.8428	1.1392
	293	2.5886	0.3528	1.0975	1.8439	1.1384
	288	2.5891	0.3541	1.0992	1.8440	1.1358
	283	2.5886	0.3552	1.1026	1.8412	1.1309
	278	2.5885	0.3561	1.1052	1.8394	1.1271
	273	2.5895	0.3570	1.1087	1.8379	1.1238
	268	2.5888	0.3580	1.1117	1.8350	1.1191
	263	2.5899	0.3589	1.1149	1.8339	1.1161
	258	2.5905	0.3598	1.1187	1.8316	1.1120
	253	2.5919	0.3608	1.1227	1.8301	1.1085
	248	2.5930	0.3618	1.1260	1.8288	1.1052
	243	2.5945	0.3626	1.1295	1.8277	1.1024
	238	2.5937	0.3635	1.1310	1.8262	1.0992
	233	2.5935	0.3643	1.1334	1.8244	1.0958
	228	0.5945	0.3655	1.1359	1.8240	1.0930
	223	2.5942	0.3666	1.1381	1.8227	1.0895
	218	2.5940	0.3675	1.1398	1.8212	1.0862
	213	2.5945	0.3682	1.1419	1.8215	1.0850
	208	2.5941	0.3690	1.1448	1.8183	1.0803
	203	2.5934	0.3704	1.1466	1.8172	1.0764
	198	2.5940	0.3714	1.1492	1.8172	1.0744
	193	2.5939	0.3722	1.1527	1.8134	1.0690
	188	2.5936	0.3732	1.1541	1.8127	1.0662
	183	2.5932	0.3739	1.1556	1.8116	1.0637
	178	2.5920	0.3749	1.1583	1.8086	1.0587
	173	2.5914	0.3759	1.1605	1.8068	1.0550
	168	2.5920	0.3765	1.1626	1.8069	1.0538
	163	2.5912	0.3771	1.1641	1.8041	1.0500
	158	2.5916	0.3780	1.1655	1.8041	1.0481
	153	2.5926	0.3790	1.1674	1.8042	1.0463
	148	2.5937	0.3792	1.1707	1.8021	1.0438
21	298	2.7376	0.3658	1.1563	1.9472	1.2156
	293	2.7417	0.3666	1.1589	1.9493	1.2162
	288	2.7465	0.3681	1.1623	1.9522	1.2161
	283	2.7507	0.3701	1.1645	1.9563	1.2162
	278	2.7532	0.3714	1.1676	1.9570	1.2141
	273	2.7546	0.3726	1.1705	1.9568	1.2115
	268	2.7572	0.3746	1.1728	1.9590	1.2098

Table 4. (Continued)

Crystal	Temp. (°K)	C^L	C'	C_{44}	C_{11}	C_{12}
21	263	2.7590	0.3754	1.1753	1.9591	1.2083
	258	2.7618	0.3768	1.1783	1.9603	1.2068
	253	2.7664	0.3782	1.1806	1.9640	1.2075
22	298	2.7232	0.3663	1.1511	1.9384	1.2059
	293	2.7292	0.3677	1.1542	1.9427	1.2073
	288	2.7306	0.3690	1.1571	1.9426	1.2045
	283	2.7355	0.3710	1.1597	1.9468	1.2047
	278	2.7384	0.3724	1.1624	1.9483	1.2035
	273	2.7397	0.3732	1.1652	1.9477	1.2012
	268	2.7456	0.3748	1.1679	1.9525	1.2029
	263	2.7470	0.3760	1.1705	1.9526	1.2006
	258	2.7523	0.3774	1.1729	1.9568	1.2020
23	298	2.7037	0.3632	1.1280	1.9388	1.2125
	293	2.7104	0.3649	1.1312	1.9440	1.2143
	288	2.7152	0.3664	1.1340	1.9476	1.2147
	283	2.7197	0.3676	1.1363	1.9510	1.2157
	278	2.7237	0.3690	1.1392	1.9535	1.2154
	273	2.7266	0.3702	1.1418	1.9550	1.2146
	268	2.7286	0.3716	1.1446	1.9556	1.2124
	263	2.7326	0.3728	1.1470	1.9584	1.2128
	258	2.7339	0.3742	1.1497	1.9584	1.2100
	253	2.7367	0.3757	1.1525	1.9598	1.2084
	248	2.7373	0.3769	1.1561	1.9582	1.2043
	243	2.7389	0.3785	1.1580	1.9556	1.2024
	238	2.7408	0.3800	1.1604	1.9604	1.2004
24	298	2.7455	0.3847	1.1281	2.0021	1.2326
25	298	2.8080	0.4034	1.1538	2.0576	1.2507
	293	2.8138	0.4048	1.1581	2.0606	1.2509
	288	2.8187	0.4063	1.1598	2.0652	1.2525
26	303	2.7936	0.4016	1.1442	2.0511	1.2478
	298	2.8019	0.4038	1.1479	2.0579	1.2502
	293	2.8106	0.4062	1.1516	2.0652	1.2528
27	298	2.7784	0.4033	1.1350	2.0467	1.2401

Table 4. (Continued)

Crystal	Temp. (^{o}K)	C_L	C'	C_{44}	C_{11}	C_{12}
28	303	2.8964	0.4139	1.1555	2.1548	1.3270
	298	2.8916	1.4164	1.1603	2.1477	1.3148
	293	2.8839	0.4190	1.1652	2.1377	1.2997

The effect of carbon and nickel on the elastic constants can be seen in Figures 3 to 8. For convenience only the ~28.5 Ni series and the ~3.12 a/o C series are shown. From Table 4 it can be seen that the same general dependence was followed at different nickel and carbon concentrations.

Although there are some ferromagnetic alloys present in this investigation, the elastic constants were measured in only the magnetically unsaturated condition. However, the ΔE effect, i.e. the change in transit time between the demagnetized and saturated states, for various ferromagnetic materials (35-38) has been reported to amount to a maximum change of 0.3% - the demagnetized transit times being larger. The error due to the ΔE effect for the ferromagnetic Fe-Ni-C alloys has therefore been assumed to be within 0.3%.

The effect that orientation errors have on the elastic constants have been studied by Waterman (39). An error of $\pm$ 0.5° in orientation would only result in a maximum error of $\pm$ 0.01% in the transit velocities.

The uncertainty in composition, as shown in Table 2, reflects both the uncertainty in the analytical chemical analysis and the sample inhomogeneity. The systematic error which this introduces to the density is included in the values of

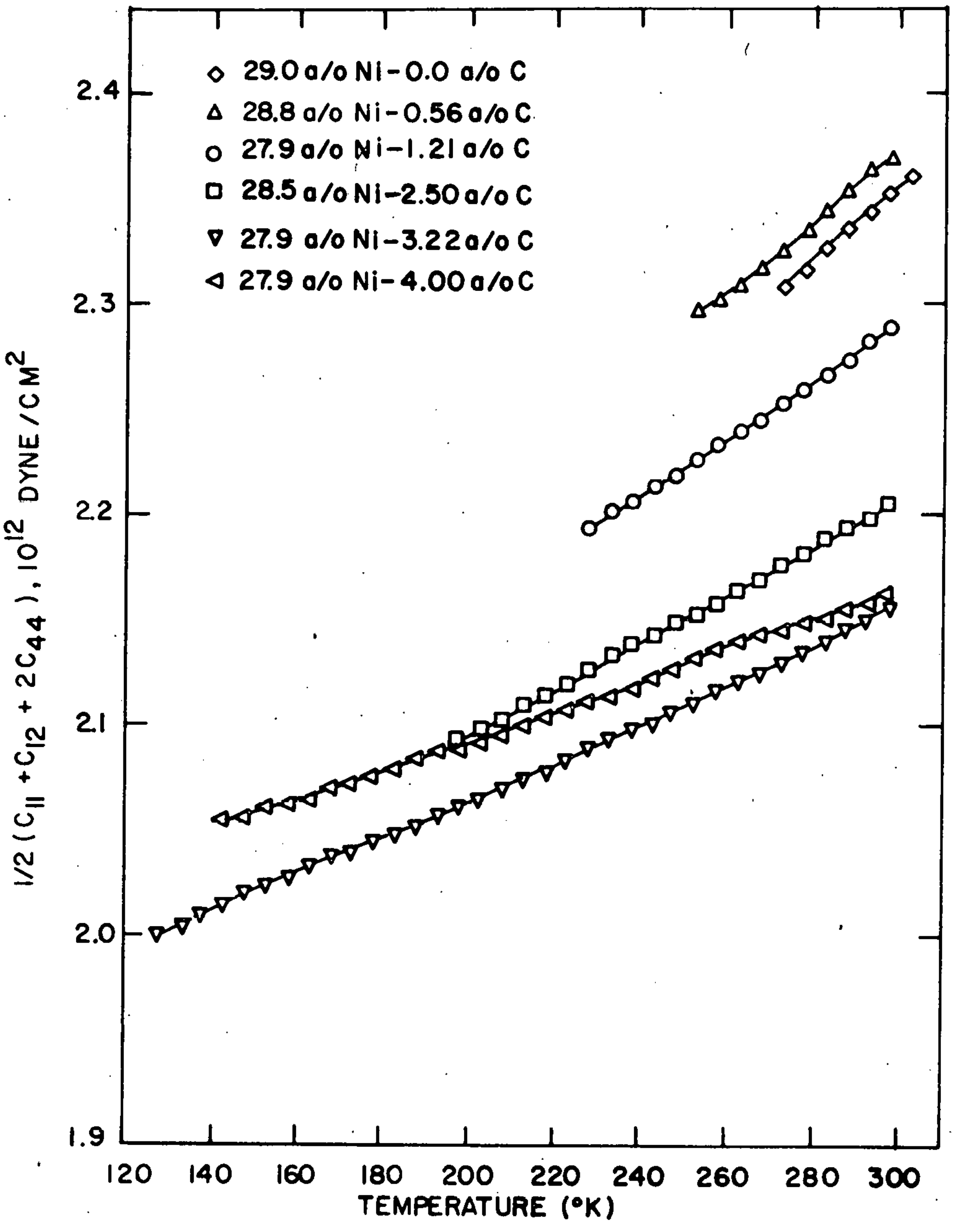

Figure 3. Effect of carbon on temperature dependence of C^L

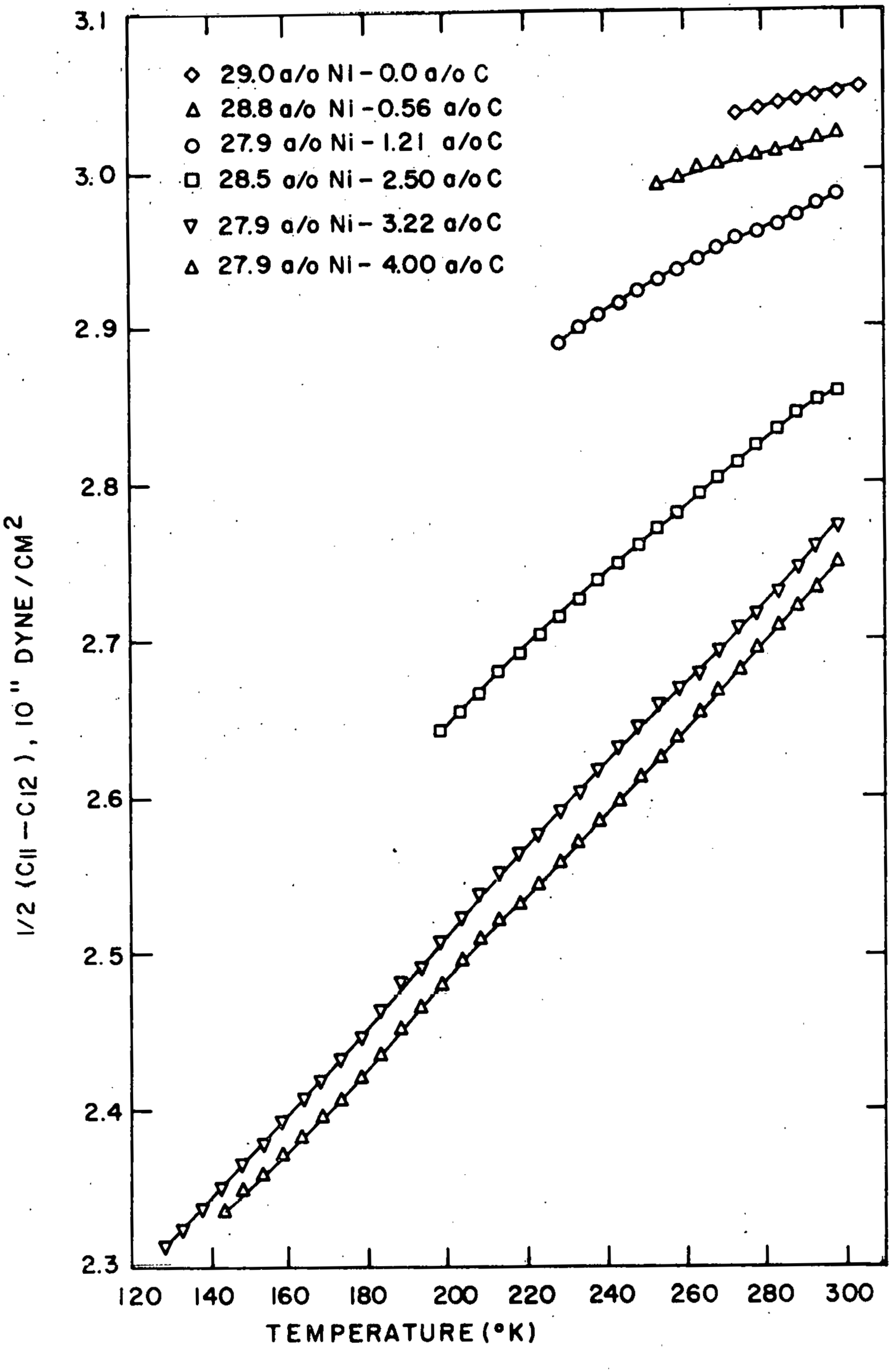

Figure 4. Effect of carbon on temperature dependence of C'

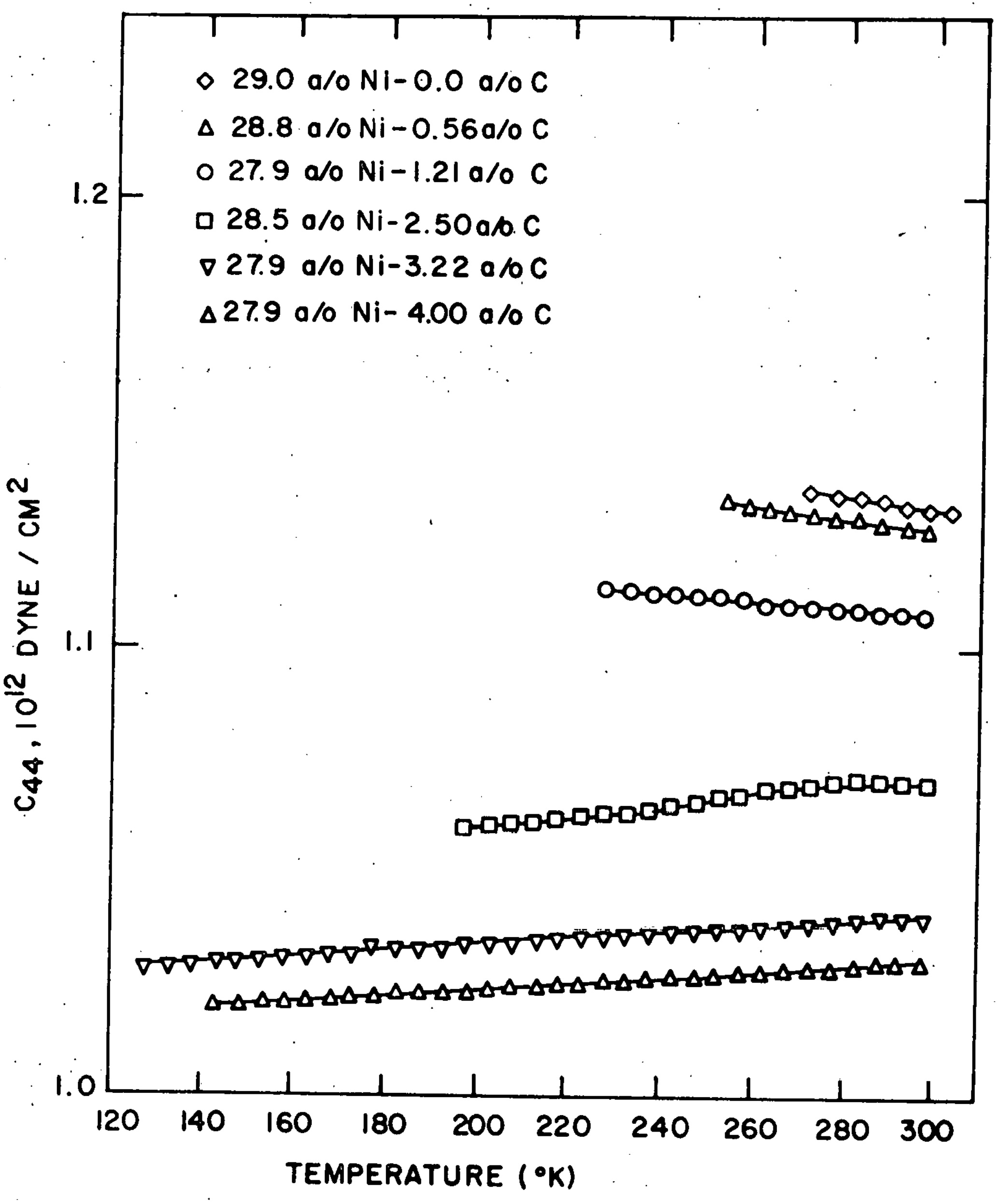

Figure 5. Effect of carbon on temperature dependence of C_{44}

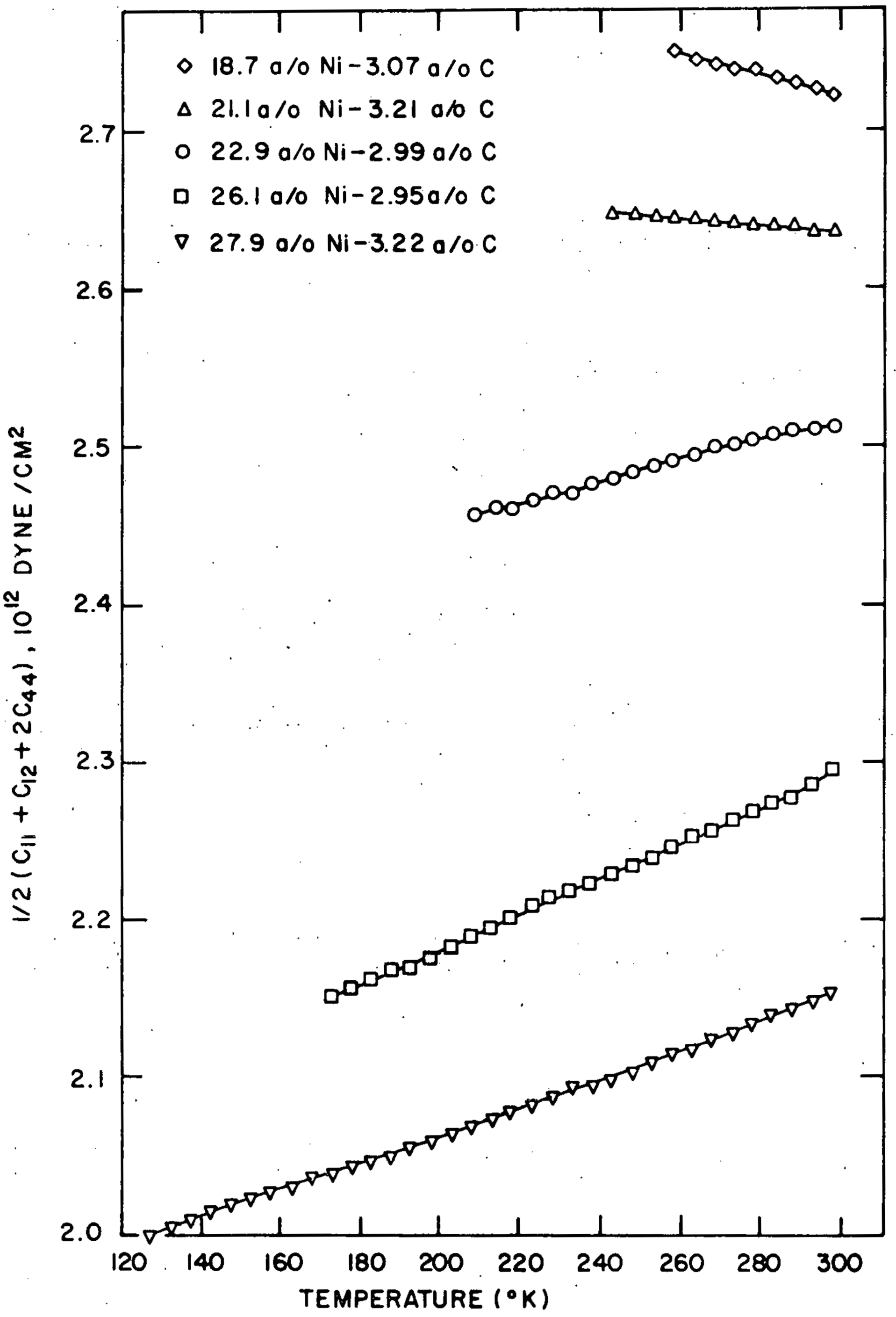

Figure 6. Effect of nickel on temperature dependence of C^L

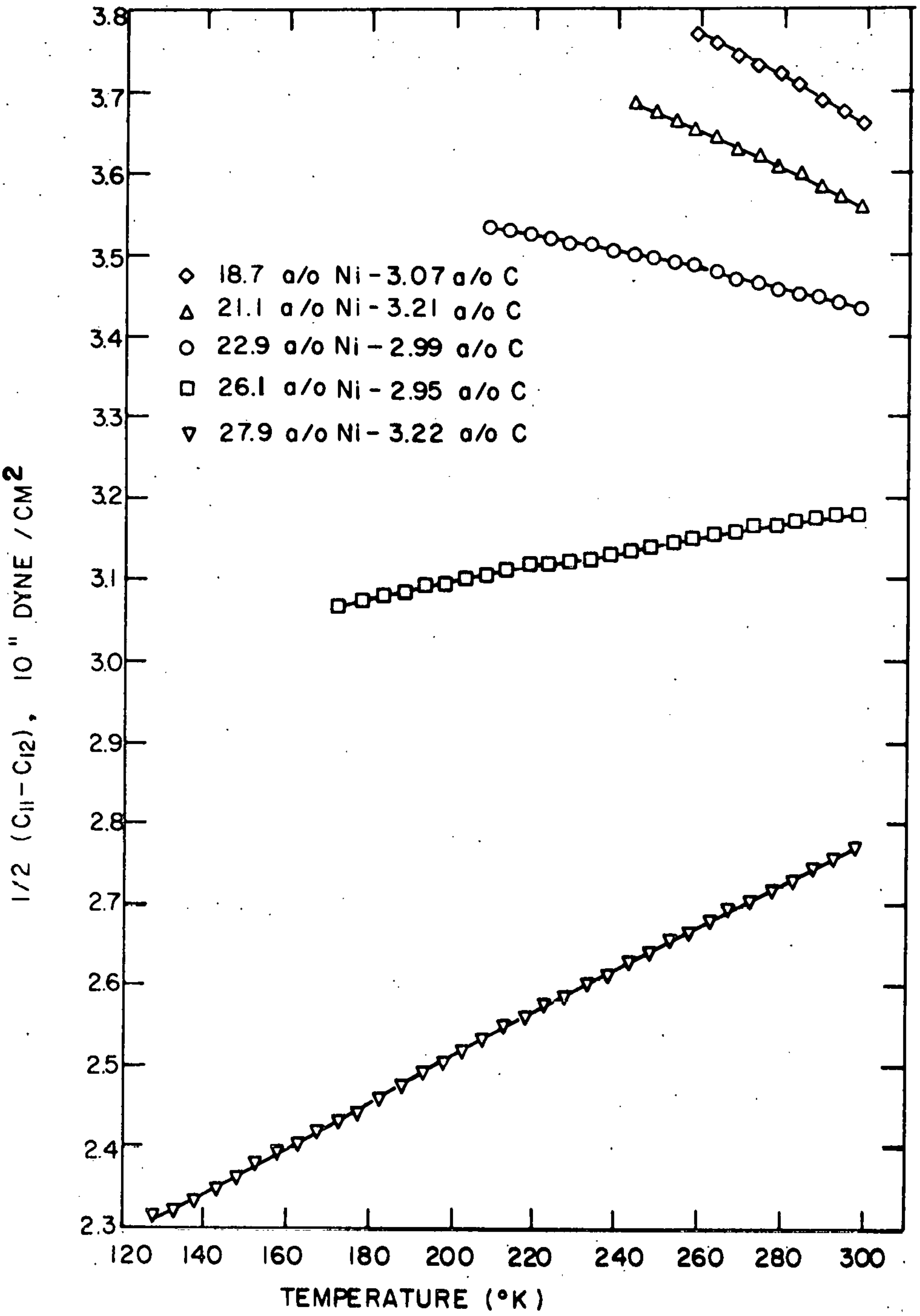

Figure 7. Effect of nickel on temperature dependence of C'

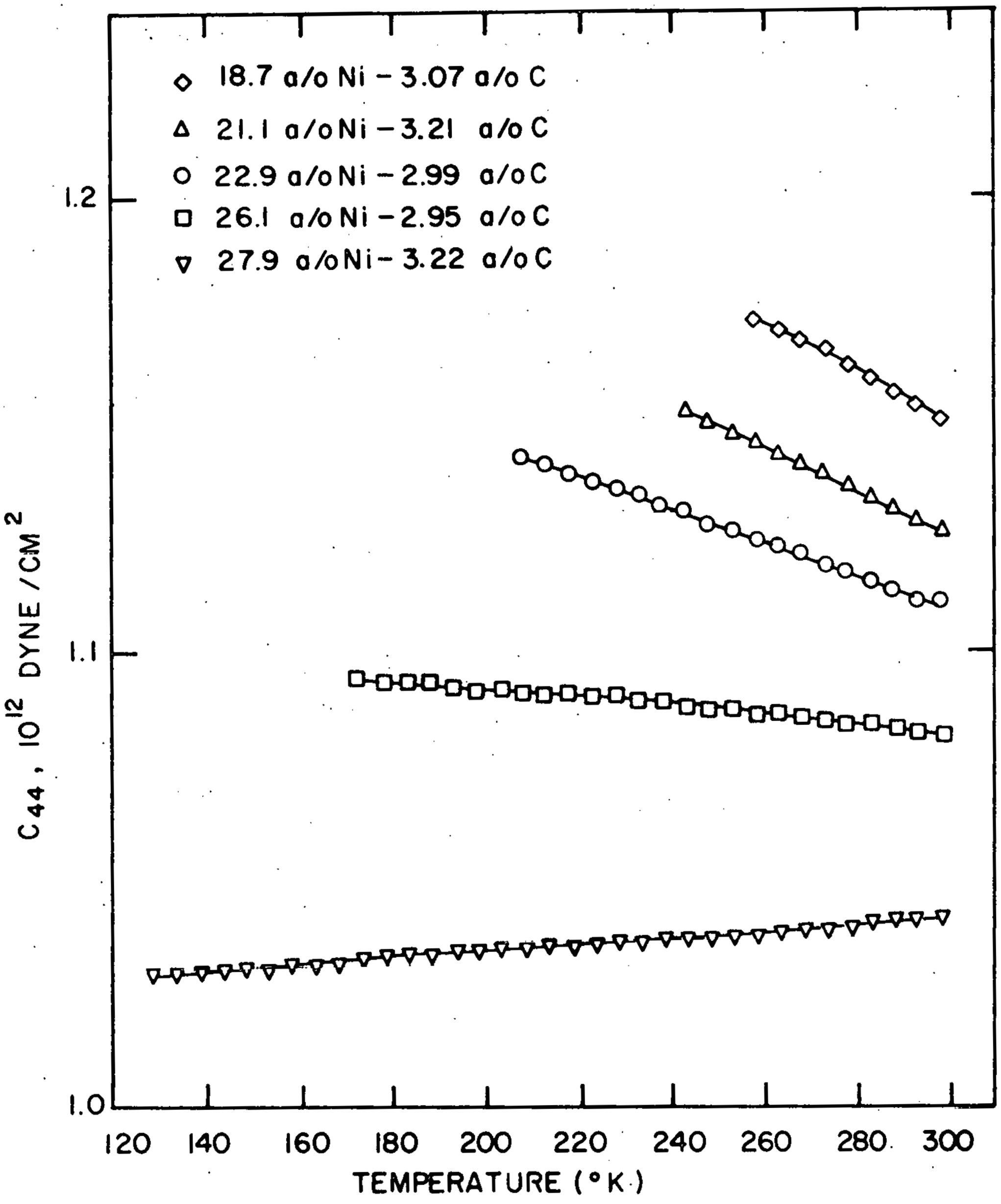

Figure 8. Effect of nickel on temperature dependence of C_{44}

the elastic constants in Table 4. The total error in the room temperature values of the elastic constants is estimated to be no more than ± 1.5%. For values below room temperature, an additional systematic error was introduced because the changes in specimen dimensions were not taken into account. Using the coefficient of thermal expansion for an iron alloy it was observed that the errors introduced by change in length and change in density tended to cancel each other when the elastic constants were calculated (Appendix B). In the temperature range over which most of these alloys were measured, this error amounts to less than 0.1% and was therefore neglected.

Table 3 gives the M_s for each alloy. It can be seen that the crystal with the "as polished" surface has a higher M_s than the crystal which was stress relieved. Since the elastic constant specimens were in the "as polished" condition, the appropriate M_s had to be used to limit the temperature range over which the temperature dependence of the elastic constants could be determined. Experience also revealed that these M_s values were only reproducible to ± 6°C. Therefore, adding a little margin for safety, the temperatures were usually lowered to within 10 or 20°C of their "as polished" M_s.

DISCUSSION

Polycrystalline Elastic Properties

In general it is not possible to calculate the elastic properties of a polycrystalline aggregate from the single crystalline elastic constants because of the constraints placed on the aggregate by the grain boundaries. However, if certain basic assumptions are made about these constraints it is possible to approximate the polycrystalline elastic properties. Voigt (40) makes the assumption that strain is uniform and the relations expressing the stress in a single crystal are averaged in terms of a homogeneous strain. Reuss (41) averages the relations expressing strain in terms of a homogeneous stress which he assumes is uniform. Both assumptions lead to the same result for the bulk modulus of a polycrystalline aggregate,

$$K = (C_{11}+2C_{12})/3. \qquad (12)$$

However, when expressions are derived for Young's modulus and the shear modulus, each theory predicts a different relationship:

$$E_V = \frac{(C_{11}+2C_{12})(C_{11}-C_{12}+3C_{44})}{2C_{11} + 3C_{12} + C_{44}} \qquad (13)$$

$$E_R = \left[\frac{3C_{11} + C_{12}}{5((C_{11}-C_{12})(C_{11}+2C_{12}))} + \frac{1}{5C_{44}}\right]^{-1} \qquad (14)$$

$$\mu_V = (C_{11}-C_{12}+3C_{44})/5 \qquad (15)$$

$$\mu_R = \left[\frac{4}{5(C_{11}-C_{12})} + \frac{3}{5C_{44}}\right]^{-1} \qquad (16)$$

where E is Young's modulus and μ is the shear modulus. Hill (42) has shown that these values represent upper and lower limits for the polycrystalline elastic properties.

These values have been calculated for all alloys at all temperatures and are listed in Table 5. Since the relationship of these properties to the martensite transformation would more than likely involve a small value for these constants, only the lower limit, the Reuss values, will be used for further discussion.

A value of $1.71\text{x}10^{12}$ dynes/cm^2 has been determined for Young's modulus from static measurements (10) for an Fe-29 a/o Ni alloy at room temperature. This compares to $E_V = 1.940\text{x}10^{12}$ dynes/cm^2 and $E_R = 1.402\text{x}10^{12}$ dynes/cm^2 from the present investigation. If the average of these values is obtained as suggested by Hill (42) a value of $1.671\text{x}10^{12}$ dynes/cm^2 results which is in excellent agreement with the

Table 5. Properties of Fe-Ni-C alloys calculated from the elastic constants; polycrystalline elastic moduli in 10^{12} dynes/cm^2; C_{12}-C_{44} in 10^{12} dynes/cm^2; and Debye temperature in ^{o}K

Crystal	Temp. (^{o}K)	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
1 (ferro)	298	0.731	0.445	1.768	1.164	1.016	-0.2021	4.45	372.7
	293	0.730	0.443	1.765	1.160	1.013	-0.2032	4.47	
	288	0.729	0.440	1.763	1.154	1.012	-0.2022	4.50	
	283	0.728	0.439	1.761	1.150	1.010	-0.2032	4.52	
	278	0.727	0.437	1.758	1.145	1.009	-0.2026	4.55	
	273	0.726	0.434	1.756	1.140	1.008	-0.2022	4.58	
2 (ferro)	298	0.801	0.543	1.940	1.402	1.119	-0.2156	3.71	405.4
	293	0.801	0.543	1.938	1.400	1.110	-0.2255	3.71	
	288	0.802	0.543	1.935	1.399	1.101	-0.2352	3.72	
	283	0.802	0.542	1.933	1.396	1.091	-0.2453	3.73	
	278	0.802	0.542	1.930	1.394	1.083	-0.2544	3.73	
	273	0.803	0.542	1.928	1.392	1.076	-0.2623	3.74	404.7
3 (ferro)	298	0.797	0.539	1.938	1.396	1.140	-0.2187	3.73	404.4
	293	0.791	0.538	1.937	1.395	1.134	-0.2194	3.73	
	288	0.798	0.538	1.935	1.392	1.125	-0.2204	3.74	
	283	0.798	0.538	1.932	1.390	1.114	-0.2216	3.75	
	278	0.798	0.538	1.929	1.388	1.104	-0.2263	3.75	
	273	0.798	0.537	1.926	1.385	1.092	-0.2386	3.76	403.6
	268	0.799	0.537	1.923	1.382	1.083	-0.2482	3.76	
	263	0.799	0.536	1.921	1.380	1.077	-0.2546	2.77	
	258	0.799	0.536	1.920	1.378	1.037	-0.2615	2.78	
	253	0.800	0.536	1.919	1.376	1.065	-0.2681	3.79	402.9

Table 5. (Continued)

Crystal	Temp. (^{o}K)	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
4 (ferro)	298	0.784	0.531	1.894	1.370	1.082	-0.2249	3.71	400.8
	293	0.784	0.531	1.891	1.367	1.074	-0.2326	3.72	
	288	0.784	0.530	1.888	1.363	1.065	-0.2410	3.73	
	283	0.784	0.529	1.886	1.360	1.058	-0.2480	3.74	
	278	0.784	0.528	1.883	1.358	1.051	-0.2549	3.74	
	273	0.784	0.528	1.880	1.356	1.045	-0.2614	3.75	399.5
	268	0.784	0.527	1.878	1.352	1.038	-0.2681	3.76	
	263	0.784	0.526	1.876	1.350	1.031	-0.2753	3.77	
	258	0.784	0.526	1.874	1.346	1.025	-0.2816	3.78	
	253	0.784	0.525	1.870	1.343	1.015	-0.2913	3.79	
	248	0.784	0.524	1.868	1.340	1.010	-0.2963	3.80	398.1
	243	0.784	0.523	1.866	1.337	1.005	-0.3016	3.81	
	238	0.784	0.522	1.862	1.333	0.998	-0.3080	3.83	
	233	0.784	0.521	1.861	1.330	0.992	-0.3145	3.84	
	228	0.783	0.520	1.858	1.326	0.984	-0.3214	3.85	396.7
5 (ferro)	298	0.757	0.510	1.826	1.315	1.039	-0.2224	3.75	392.9
	293	0.757	0.510	1.824	1.313	1.033	-0.2285	3.75	
	288	0.756	0.510	1.822	1.312	1.027	-0.2338	3.75	
	283	0.756	0.507	1.819	1.305	1.023	-0.2362	3.78	
	278	0.755	0.505	1.815	1.301	1.017	-0.2409	3.79	
	273	0.754	0.504	1.812	1.298	1.013	-0.2440	3.80	391.0
	268	0.754	0.503	1.809	1.294	1.007	-0.2490	3.81	
	263	0.753	0.502	1.806	1.290	1.001	-0.2536	3.82	
	258	0.752	0.500	1.802	1.285	0.997	-0.2562	3.84	
	253	0.751	0.498	1.799	1.281	0.994	-0.2576	3.85	
	248	0.750	0.497	1.796	1.278	0.990	-0.2599	3.86	388.6
	243	0.749	0.496	1.793	1.273	0.985	-0.2631	3.87	

Table 5. (Continued)

Crystal	Temp. (^oK)	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
5	238	0.748	0.494	1.790	1.269	0.983	-0.2635	3.88	
	233	0.747	0.492	1.787	1.265	0.978	-0.2673	3.90	
	228	0.746	0.490	1.783	1.260	0.972	-0.2724	3.91	
	223	0.746	0.489	1.779	1.256	0.966	-0.2767	3.93	386.0
	218	0.745	0.488	1.776	1.251	0.962	-0.2791	3.94	
	213	0.744	0.486	1.773	1.247	0.957	-0.2827	3.96	
	208	0.743	0.484	1.769	1.242	0.953	-0.2854	3.98	
	203	0.742	0.482	1.766	1.237	0.948	-0.2895	3.99	
	198	0.741	0.481	1.763	1.233	0.945	-0.2907	4.00	383.4
6 (ferro)	298	0.735	0.495	1.780	1.280	1.024	-0.2019	3.75	387.3
	293	0.735	0.494	1.777	1.275	1.019	-0.2054	3.77	
	288	0.734	0.492	1.774	1.270	1.013	-0.2102	3.79	
	283	0.733	0.490	1.771	1.265	1.010	-0.2122	3.81	
	278	0.732	0.488	1.768	1.260	1.006	-0.2145	3.82	
	273	0.732	0.487	1.765	1.257	1.002	-0.2179	3.84	384.8
	268	0.731	0.485	1.762	1.252	0.998	-0.2200	3.85	
	263	0.730	0.483	1.759	1.247	0.994	-0.2226	3.87	
	258	0.729	0.481	1.757	1.243	0.990	-0.2250	3.89	
	253	0.729	0.480	1.754	1.239	0.985	-0.2302	3.90	
	248	0.728	0.478	1.751	1.235	0.981	-0.2327	3.92	382.2
	243	0.727	0.476	1.748	1.229	0.977	-0.2354	3.94	
	238	0.727	0.475	1.746	1.225	0.974	-0.2373	3.96	
	233	0.726	0.473	1.744	1.220	0.971	-0.2388	3.98	
	228	0.726	0.471	1.741	1.216	0.968	-0.2418	4.00	
	223	0.725	0.469	1.738	1.210	0.961	-0.2469	4.02	379.5
	218	0.724	0.468	1.735	1.207	0.957	-0.2498	4.04	
	213	0.723	0.466	1.732	1.202	0.954	-0.2511	4.06	

Table 5. (Continued)

Crystal	Temp. (^{o}K)	μ_V	μ_R	E_V	E_R	K	$C_{12}-C_{44}$	A	Debye temp.
6	208	0.722	0.464	1.729	1.197	0.951	-0.2530	4.08	
	203	0.722	0.462	1.727	1.192	0.948	-0.2554	4.10	
	198	0.721	0.459	1.724	1.186	0.944	-0.2569	4.13	376.6
	193	0.720	0.457	1.721	1.181	0.940	-0.2596	4.15	
	188	0.719	0.456	1.718	1.178	0.936	-0.2630	4.16	
	183	0.718	0.454	1.715	1.171	0.932	-0.2649	4.19	
	178	0.718	0.451	1.713	1.166	0.931	-0.2651	4.22	
	173	0.717	0.449	1.710	1.160	0.927	-0.2672	4.24	373.5
	168	0.716	0.448	1.708	1.156	0.926	-0.2676	4.26	
	163	0.715	0.446	1.704	1.151	0.921	-0.2709	4.28	
	158	0.714	0.444	1.702	1.147	0.919	-0.2714	4.30	
	153	0.714	0.442	1.700	1.142	0.917	-0.2723	4.33	
	148	0.713	0.440	1.697	1.137	0.914	-0.2736	4.36	391.3
	143	0.712	0.438	1.695	1.132	0.913	-0.2737	4.38	
	138	0.711	0.436	1.693	1.128	0.910	-0.2749	4.41	
	133	0.711	0.434	1.690	1.123	0.906	-0.2785	4.43	
	128	0.710	0.432	1.687	1.119	0.903	-0.2806	4.45	
7 (ferro)	298	0.728	0.491	1.771	1.272	1.039	-0.1755	3.75	386.3
	293	0.727	0.489	1.768	1.268	1.038	-0.1737	3.76	
	288	0.727	0.487	1.767	1.264	1.036	-0.1755	3.78	
	283	0.727	0.486	1.766	1.259	1.030	-0.1822	3.81	
	278	0.728	0.484	1.766	1.255	1.025	-0.1885	3.84	
	273	0.728	0.483	1.765	1.251	1.022	-0.1918	3.86	383.8
	268	0.727	0.481	1.763	1.246	1.021	-0.1904	3.88	
	263	0.727	0.479	1.762	1.243	1.017	-0.1949	3.90	
	258	0.727	0.477	1.760	1.238	1.014	-0.1972	3.92	

Table 5. (Continued)

Crystal	Temp.	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
7	253	0.726	0.475	1.758	1.233	1.012	-0.1981	3.94	
	248	0.725	0.474	1.754	1.228	1.006	-0.2033	3.96	381.2
	243	0.724	0.471	1.752	1.223	1.002	-0.2051	3.98	
	238	0.724	0.470	1.749	1.218	0.997	-0.2094	4.00	
	233	0.723	0.468	1.746	1.214	0.995	-0.2107	4.02	
	228	0.723	0.466	1.745	1.209	0.992	-0.2128	4.04	
	223	0.722	0.464	1.743	1.205	0.991	-0.2130	4.07	378.7
	218	0.722	0.463	1.741	1.201	0.986	-0.2166	4.09	
	213	0.721	0.461	1.738	1.196	0.981	-0.2214	4.10	
	208	0.721	0.460	1.737	1.194	0.978	-0.2232	4.12	
	203	0.720	0.458	1.734	1.188	0.975	-0.2254	4.14	
	198	0.719	0.456	1.731	1.184	0.975	-0.2231	4.16	376.1
	193	0.717	0.454	1.728	1.178	0.974	-0.2190	4.18	
	188	0.716	0.452	1.725	1.174	0.972	-0.2217	4.20	
	183	0.716	0.450	1.723	1.168	0.968	-0.2245	4.23	
	178	0.715	0.448	1.721	1.163	0.966	-0.2262	4.26	
	173	0.714	0.445	1.718	1.157	0.962	-0.2282	4.29	372.9
	168	0.714	0.444	1.716	1.154	0.959	-0.2300	4.30	
	163	0.713	0.442	1.714	1.150	0.959	-0.2294	4.32	
	158	0.712	0.440	1.712	1.145	0.959	-0.2282	4.34	
	153	0.712	0.439	1.711	1.142	0.958	-0.2274	4.36	
	148	0.711	0.437	1.710	1.138	0.958	-0.2265	4.38	370.7
	143	0.710	0.436	1.709	1.135	0.958	-0.2256	4.40	
8	298	0.826	0.572	2.007	1.477	1.175	-0.2021	3.57	
	293	0.827	0.573	2.006	1.476	1.165	-0.2128	3.57	
	288	0.828	0.573	2.004	1.475	1.153	-0.2268	3.57	

Table 5. (Continued)

Crystal	Temp.	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
9 (ferro)	298	0.824	0.572	2.002	1.475	1.169	-0.2044	3.56	414.3
	293	0.826	0.573	2.002	1.476	1.162	-0.2143	3.56	
	288	0.827	0.573	2.002	1.476	1.153	-0.2251	3.56	
	283	0.828	0.575	2.002	1.477	1.148	-0.2326	3.56	
	278	0.830	0.576	2.003	1.478	1.141	-0.2417	3.56	
	273	0.830	0.576	2.003	1.479	1.135	-0.2492	3.56	415.3
	268	0.832	0.577	2.002	1.478	1.125	-0.2610	3.56	
	263	0.833	0.578	2.002	1.479	1.120	-0.2684	3.56	415.5
10 (ferro)	298	0.809	0.565	1.968	1.457	1.150	-0.2000	3.52	411.4
	293	0.810	0.566	1.968	1.458	1.145	-0.2074	3.52	
	288	0.811	0.566	1.968	1.458	1.139	-0.2147	3.52	
	283	0.812	0.567	1.969	1.459	1.133	-0.2222	3.52	
	278	0.813	0.568	1.969	1.459	1.127	-0.2296	3.52	
	273	0.814	0.569	1.969	1.460	1.122	-0.2369	3.52	412.2
	268	0.815	0.569	1.969	1.460	1.116	-0.2440	3.52	
	263	0.816	0.570	1.969	1.460	1.110	-0.2515	3.52	
	258	0.817	0.570	1.968	1.460	1.105	-0.2584	3.52	
	253	0.818	0.570	1.968	1.460	1.099	-0.2657	3.52	412.6
11 (ferro)	298	0.790	0.555	1.922	1.430	1.128	-0.1884	3.48	407.0
	293	0.790	0.555	1.920	1.428	1.119	-0.1985	3.48	
	288	0.791	0.554	1.918	1.427	1.114	-0.2039	3.49	
	283	0.791	0.554	1.918	1.426	1.111	-0.2078	3.49	
	278	0.792	0.554	1.917	1.425	1.105	-0.2139	3.50	
	273	0.792	0.554	1.917	1.424	1.103	-0.2171	3.50	406.6
	268	0.792	0.554	1.917	1.423	1.101	-0.2201	3.51	
	263	0.793	0.554	1.916	1.422	1.095	-0.2257	3.51	

Table 5. (Continued)

Crystal	Temp. (^{o}K)	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
11	258	0.793	0.554	1.915	1.420	1.090	-0.2314	3.52	
	253	0.793	0.553	1.914	1.419	1.087	-0.2356	3.52	
	248	0.794	0.553	1.912	1.417	1.081	-0.2414	3.53	406.2
	243	0.794	0.553	1.908	1.414	1.066	-0.2572	3.53	
	238	0.794	0.552	1.904	1.411	1.055	-0.2681	3.54	
	233	0.794	0.552	1.903	1.409	1.051	-0.2727	3.54	
	228	0.794	0.552	1.903	1.408	1.048	-0.2759	3.55	
	223	0.795	0.552	1.902	1.407	1.044	-0.2812	3.56	405.4
	218	0.795	0.552	1.900	1.405	1.036	-0.2895	3.56	
	213	0.795	0.551	1.899	1.404	1.033	-0.2928	3.56	
	208	0.796	0.551	1.898	1.402	1.028	-0.2980	3.57	
	203	0.796	0.551	1.897	1.401	1.025	-0.3021	3.58	405.1
12 (ferro)	298	0.776	0.552	1.888	1.420	1.109	-0.1851	3.40	404.8
	293	0.776	0.552	1.885	1.418	1.099	-0.1946	3.40	
	288	0.777	0.552	1.884	1.416	1.090	-0.2057	3.41	
	283	0.777	0.551	1.882	1.414	1.086	-0.2093	3.42	
	278	0.777	0.551	1.881	1.413	1.082	-0.2134	3.42	
	273	0.777	0.550	1.879	1.410	1.075	-0.2201	3.42	404.0
	268	0.778	0.550	1.877	1.408	1.068	-0.2286	3.43	
	263	0.778	0.550	1.876	1.406	1.062	-0.2349	3.44	
	258	0.777	0.549	1.873	1.404	1.058	-0.2366	3.44	
	253	0.777	0.548	1.870	1.401	1.051	-0.2444	3.45	
	248	0.777	0.548	1.868	1.399	1.045	-0.2505	3.46	403.0
	243	0.778	0.548	1.867	1.397	1.038	-0.2584	3.46	
	238	0.779	0.547	1.866	1.394	1.031	-0.2674	3.48	
	233	0.779	0.546	1.865	1.392	1.026	-0.2718	3.49	
	228	0.779	0.546	1.864	1.391	1.022	-0.2767	3.49	

Table 5. (Continued)

Crystal	Temp. (^{o}K)	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
12	223	0.779	0.546	1.862	1.389	1.016	-0.2820	3.50	402.3
	218	0.779	0.546	1.859	1.387	1.008	-0.2907	3.50	
	213	0.779	0.545	1.856	1.384	1.002	-0.2966	3.50	
	208	0.779	0.544	1.853	1.381	0.997	-0.3010	3.51	
	203	0.779	0.544	1.852	1.378	0.989	-0.3100	3.52	
	198	0.779	0.543	1.848	1.376	0.982	-0.3163	3.52	401.1
	193	0.779	0.542	1.846	1.373	0.977	-0.3210	3.53	
	188	0.779	0.542	0.845	1.370	0.972	-0.3264	3.54	
	183	0.779	0.541	1.842	1.368	0.967	-0.3311	3.55	
	178	0.779	0.540	1.840	1.365	0.961	-0.3375	3.56	
	173	0.780	0.540	1.839	1.363	0.952	-0.3488	3.57	400.2
13 (para)	298	0.833	0.599	2.067	1.562	1.327	-0.0622	3.33	422.8
	293	0.837	0.605	2.074	1.576	1.325	-0.0697	3.29	
	288	0.839	0.607	2.076	1.578	1.317	-0.0805	3.29	
	283	0.840	0.608	2.078	1.580	1.314	-0.0862	3.29	
	278	0.842	0.609	2.081	1.582	1.314	-0.0891	3.29	
	273	0.842	0.610	2.093	1.584	1.304	-0.0880	3.31	426.4
	268	0.843	0.611	2.099	1.586	1.354	-0.0888	3.31	
14 (para)	298	0.816	0.592	2.035	1.546	1.337	-0.0241	3.28	419.7
	293	0.818	0.593	2.038	1.549	1.332	-0.0317	3.28	
	288	0.820	0.594	2.041	1.552	1.329	-0.0388	3.28	
	283	0.822	0.596	2.043	1.554	1.326	-0.0441	3.28	
	278	0.823	0.597	2.045	1.556	1.323	-0.0494	3.27	
	273	0.825	0.598	2.048	1.559	1.317	-0.0575	3.27	421.6
	268	0.826	0.600	2.050	1.562	1.313	-0.0641	3.27	

Table 5. (Continued)

Crystal	Temp. (^oK)	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
14	263	0.828	0.601	2.052	1.563	1.309	-0.0706	3.27	
	258	0.830	0.602	2.054	1.565	1.305	-0.0782	3.27	
	253	0.831	0.603	2.056	1.568	1.301	-0.0846	3.27	
	248	0.833	0.605	2.058	1.570	1.298	-0.0898	3.26	423.4
	243	0.834	0.606	2.060	1.572	1.294	-0.0967	3.26	
15 (ferro)	298	0.803	0.587	1.996	1.528	1.291	-0.0486	3.23	417.0
	293	0.805	0.588	1.997	1.530	1.286	-0.0553	3.23	
	288	0.806	0.589	1.999	1.532	1.283	-0.0604	3.23	
	283	0.807	0.589	2.001	1.533	1.278	-0.0674	3.23	
	278	0.809	0.591	2.002	1.535	1.274	-0.0743	3.23	
	273	0.810	0.592	2.004	1.536	1.268	-0.0830	3.23	418.4
	268	0.812	0.593	2.005	1.538	1.263	-0.0901	3.23	
	263	0.813	0.594	2.006	1.539	1.256	-0.0986	3.22	
	258	0.814	0.595	2.007	1.541	1.251	-0.1065	3.22	
	253	0.816	0.596	2.009	1.542	1.246	-0.1138	3.22	
	248	0.817	0.597	2.009	1.543	1.239	-0.1224	3.22	419.6
	243	0.818	0.598	2.010	1.544	1.233	-0.1304	3.22	
	238	0.820	0.599	2.011	1.545	1.228	-0.1383	3.23	
	233	0.821	0.600	2.012	1.546	1.221	-0.1467	3.23	
	228	0.822	0.600	2.013	1.547	1.218	-0.1522	3.23	
	223	0.823	0.601	2.014	1.548	1.213	-0.1589	3.23	420.7
	218	0.824	0.602	2.014	1.548	1.206	-0.1678	3.23	
	213	0.826	0.603	2.016	1.549	1.204	-0.1721	3.23	
	208	0.827	0.603	2.016	1.550	1.197	-0.1810	3.23	421.4

Table 5. (Continued)

Crystal	Temp. (^oK)	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
16 (ferro)	298	0.791	0.581	1.945	1.500	1.200	-0.1108	3.19	413.3
	293	0.791	0.581	1.945	1.500	1.196	-0.1185	3.19	
	288	0.793	0.582	1.945	1.499	1.151	-0.1232	3.19	
	283	0.794	0.583	1.943	1.499	1.173	-0.1410	3.20	
	278	0.794	0.583	1.942	1.499	1.164	-0.1504	3.20	
	273	0.795	0.584	1.939	1.498	1.153	-0.1598	3.20	413.7
	268	0.796	0.584	1.938	1.498	1.145	-0.1722	3.20	
	263	0.796	0.584	1.937	1.497	1.136	-0.1810	3.20	
	258	0.797	0.585	1.936	1.496	1.132	-0.1913	3.20	
	253	0.798	0.585	1.934	1.495	1.122	-0.1959	3.20	
	248	0.798	0.586	1.934	1.495	1.117	-0.2075	3.20	414.0
	243	0.799	0.586	1.933	1.494	1.110	-0.2137	3.20	
	238	0.800	0.586	1.932	1.493	1.102	-0.2212	3.21	
	233	0.800	0.586	1.932	1.493	1.098	-0.2312	3.21	
	228	0.801	0.587	1.931	1.493	1.093	-0.2354	3.21	
	223	0.802	0.587	1.930	1.492	1.087	-0.2424	3.21	414.1
	218	0.802	0.587	1.929	1.491	1.078	-0.2591	3.22	
	213	0.803	0.587	1.929	1.490	1.075	-0.2640	3.22	
	208	0.803	0.587	1.929	1.490	1.073	-0.2664	3.22	
	203	0.804	0.588	1.928	1.489	1.067	-0.2731	3.22	
	198	0.805	0.588	1.928	1.489	1.064	-0.2771	3.23	414.2
	193	0.805	0.588	1.927	1.489	1.059	-0.2832	3.23	
	188	0.805	0.588	1.927	1.488	1.057	-0.2852	3.23	
	183	0.806	0.588	1.927	1.488	1.052	-0.2911	3.23	
	178	0.807	0.589	1.927	1.488	1.049	-0.2959	3.24	
	173	0.808	0.589	1.927	1.488	1.045	-0.3012	3.24	414.4
	168	0.808	0.589	1.926	1.486	1.040	-0.3073	3.24	

Table 5. (Continued)

Crystal	Temp. (^oK)	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
16	163	0.809	0.589	1.926	1.486	1.037	-0.3113	3.24	
	158	0.809	0.589	1.925	1.485	1.033	-0.3154	3.25	
	153	0.810	0.589	1.924	1.484	1.028	-0.3223	3.25	
	148	0.811	0.590	1.924	1.484	1.025	-0.3266	3.25	414.4
	143	0.811	0.590	1.924	1.484	1.020	-0.3325	3.26	
	138	0.812	0.590	1.923	1.483	1.016	-0.3367	3.26	
	133	0.812	0.590	1.923	1.482	1.013	-0.3411	3.26	
	128	0.813	0.590	1.923	1.482	1.009	-0.3459	3.26	
	123	0.814	0.591	1.923	1.482	1.006	-0.3508	3.27	
	118	0.814	0.591	1.922	1.481	1.001	-0.3559	3.27	414.6
17	303	0.844	0.612	2.116	1.608	1.430	0.0230	3.27	427.9
	298	0.846	0.614	2.120	1.612	1.431	0.0213	3.27	428.4
	293	0.849	0.616	2.126	1.617	1.430	0.0152	3.27	429.1
18 (para)	298	0.834	0.607	2.090	1.592	1.410	0.0197	3.25	425.6
	293	0.836	0.609	2.094	1.596	1.407	0.0130	3.25	
	288'	0.839	0.611	2.098	1.601	1.405	0.0072	3.24	
	283	0.840	0.612	2.102	1.604	1.404	0.0034	3.24	
	278	0.842	0.614	2.106	1.609	1.403	-0.0012	3.24	
	273	0.844	0.616	2.110	1.613	1.402	-0.0050	3.23	428.4
	268	0.847	0.618	2.115	1.616	1.400	-0.0116	3.23	
	263	0.849	0.620	2.118	1.622	1.400	-0.0143	3.22	
	258	0.850	0.622	2.121	1.624	1.400	-0.0175	3.22	
	253	0.852	0.623	2.125	1.628	1.399	-0.0216	3.22	
	248	0.854	0.625	2.129	1.632	1.398	-0.0262	3.22	431.2

Table 5. (Continued)

Crystal	Temp. (^{o}K)	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
19 (para)	298	0.818	0.604	2.052	1.582	1.393	0.0300	3.16	423.0
	293	0.820	0.606	2.056	1.586	1.391	0.0243	3.16	
	288	0.822	0.607	2.060	1.590	1.390	0.0198	3.15	
	283	0.824	0.609	2.064	1.594	1.388	0.0141	3.15	
	278	0.826	0.611	2.067	1.598	1.386	0.0100	3.15	
	273	0.828	0.612	2.070	1.601	1.385	0.0053	3.14	425.7
	268	0.830	0.614	2.075	1.605	1.382	-0.0127	3.14	
	263	0.831	0.616	2.077	1.609	1.381	-0.0432	3.14	
	258	0.833	0.618	2.081	1.612	1.379	-0.0955	3.14	
	253	0.835	0.619	2.084	1.616	1.378	-0.1387	3.13	
	248	0.837	0.621	2.088	1.619	1.376	-0.1972	3.13	428.1
	243	0.839	0.623	2.091	1.623	1.374	-0.2432	3.13	
20 (para)	298	0.798	0.594	2.006	1.556	1.374	0.0438	3.11	415.2
	293	0.800	0.595	2.009	1.560	1.374	0.0409	3.11	
	288	0.801	0.597	2.012	1.564	1.372	0.0366	3.10	
	283	0.804	0.599	2.016	1.567	1.368	0.0282	3.10	
	278	0.806	0.600	2.019	1.570	1.365	0.0219	3.10	
	273	0.808	0.602	2.024	1.574	1.362	0.0151	3.10	421.3
	268	0.810	0.603	2.027	1.577	1.358	0.0074	3.10	
	263	0.812	0.605	2.032	1.580	1.355	0.0012	3.11	
	258	0.815	0.607	2.036	1.583	1.352	-0.0067	3.11	
	253	0.818	0.609	2.041	1.587	1.349	-0.0142	3.11	
	248	0.820	0.610	2.046	1.591	1.346	-0.0208	3.11	423.9
	243	0.823	0.612	0.050	1.594	1.344	-0.0270	3.11	
	238	0.824	0.613	2.052	1.596	1.342	-0.0317	3.11	
	233	0.826	0.614	2.055	1.599	1.339	-0.0376	3.11	

Table 5. (Continued)

Crystal	Temp. (^{o}K)	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
20	228	0.828	0.616	2.058	1.603	1.337	-0.0429	3.11	
	223	0.829	0.618	2.061	1.606	1.334	-0.0486	3.10	426.1
	218	0.831	0.619	2.063	1.608	1.331	-0.0536	3.10	
	213	0.832	0.620	2.066	1.611	1.331	-0.0569	3.10	
	208	0.834	0.622	2.069	1.613	1.326	-0.0646	3.10	
	203	0.836	0.624	2.072	1.617	1.323	-0.0701	3.10	
	198	0.838	0.625	2.076	1.620	1.322	-0.0748	3.09	428.2
	193	0.840	0.627	2.079	1.623	1.317	-0.0837	3.10	
	188	0.842	0.628	2.081	1.626	1.315	-0.0878	3.09	
	183	0.843	0.629	2.083	1.628	1.313	-0.0918	3.09	
	178	0.845	0.631	2.086	1.631	1.309	-0.0996	3.09	
	173	0.847	0.632	2.088	1.634	1.306	-0.1055	3.09	430.2
	168	0.848	0.633	2.091	1.636	1.305	-0.1088	3.09	
	163	0.849	0.634	2.093	1.637	1.301	-0.1141	3.09	
	158	0.850	0.636	2.095	1.640	1.300	-0.1174	3.08	
	153	0.852	0.637	2.097	1.643	1.299	-0.1212	3.08	
	148	0.854	0.638	2.101	1.644	1.297	-0.1269	3.09	431.8
21 (para)	298	0.840	0.620	2.114	1.630	1.459	0.0593	3.16	429.5
	293	0.842	0.622	2.119	1.633	1.461	0.0573	3.16	
	288	0.845	0.624	2.125	1.638	1.461	0.0537	3.16	
	283	0.847	0.626	2.129	1.645	1.463	0.0517	3.15	
	278	0.849	0.629	2.134	1.649	1.462	0.0465	3.14	
	273	0.851	0.630	2.138	1.653	1.460	0.0410	3.14	432.5
	268	0.854	0.633	2.143	1.659	1.460	0.0370	3.13	
	263	0.855	0.634	2.147	1.662	1.459	0.0330	3.13	
	258	0.858	0.636	2.151	1.667	1.458	0.0285	3.13	
	253	0.860	0.639	2.156	1.672	1.460	0.0269	3.12	434.9

Table 5. (Continued)

Crystal	Temp. (^oK)	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
22 (para)	298	0.837	0.620	2.106	1.628	1.450	0.0547	3.14	429.1
	293	0.840	0.622	2.112	1.633	1.452	0.0531	3.14	
	288	0.842	0.624	2.116	1.637	1.450	0.0474	3.14	
	283	0.844	0.627	2.122	1.644	1.452	0.0450	3.13	
	278	0.846	0.629	2.126	1.648	1.452	0.0411	3.12	
	273	0.848	0.630	2.130	1.652	1.450	0.0360	3.12	432.2
	268	0.851	0.632	2.135	1.657	1.453	0.0351	3.12	
	263	0.853	0.634	2.139	1.661	1.451	0.0316	3.11	
	258	0.855	0.636	2.144	1.666	1.454	0.0290	3.11	434.0
23 (para)	298	0.822	0.612	2.075	1.611	1.455	0.0844	3.11	426.0
	293	0.825	0.615	2.081	1.617	1.458	0.0831	3.10	
	288	0.827	0.617	2.087	1.622	1.459	0.0807	3.09	
	283	0.829	0.619	2.091	1.627	1.461	0.0794	3.09	
	278	0.831	0.621	2.096	1.632	1.461	0.0762	3.09	
	273	0.833	0.623	2.100	1.636	1.461	0.0728	3.08	429.2
	268	0.835	0.625	2.105	1.640	1.460	0.0678	3.08	
	263	0.837	0.627	2.109	1.645	1.461	0.0658	3.08	
	258	0.840	0.629	2.113	1.649	1.459	0.0602	3.07	
	253	0.842	0.631	2.118	1.654	1.459	0.0559	3.07	
	248	0.844	0.633	2.123	1.658	1.456	0.0482	3.07	432.2
	243	0.846	0.635	2.127	1.663	1.455	0.0441	3.06	
	238	0.848	0.637	2.130	1.668	1.454	0.0400	3.05	433.3
24 (para)	298	0.831	0.636	2.102	1.671	1.489	0.1045	2.93	429.9

Table 5. (Continued)

Crystal	Temp. (^oK)	μ_V	μ_R	E_V	E_R	K	C_{12}-C_{44}	A	Debye temp.
25	298	0.854	0.662	2.157	1.733	1.520	0.0970	2.86	439.6
	293	0.857	0.664	2.164	1.739	1.521	0.0927	2.86	
	288	0.858	0.666	2.168	1.744	1.523	0.0927	2.85	
26	303	0.847	0.658	2.142	1.724	1.516	0.1037	2.85	438.1
	298	0.850	0.661	2.150	1.731	1.519	0.1024	2.84	439.0
	293	0.853	0.664	2.158	1.740	1.524	0.1012	2.84	440.0
27 (para)	298	0.842	0.658	2.131	1.723	1.509	0.1050	2.81	436.6
28	303	0.859	0.673	2.186	1.771	1.603	0.1715	2.79	443.2
	298	0.863	0.677	2.192	1.778	1.592	0.1545	2.79	444.1
	293	0.867	0.680	2.198	1.785	1.579	0.1345	2.78	445.1

direct determination. The same temperature dependence is observed in both investigations. Similarly a value of 1.80x 10^{12} dynes/cm^2 was obtained from a polycrystalline alloy (10) comparable to the composition of crystal no. 13 of this investigation for which Hill's averaging technique gives a value of 1.814x10^{12} dynes/cm^2. The agreement is excellent and again the same temperature dependence was observed in both investigations.

The decrease in Young's modulus with increasing temperature ($dE/dT < 0$) is the behavior displayed by most metals. An inspection of the values in Table 5 shows that many of the alloys in this investigation have $dE/dT > 0$. Other authors (10,43) have also observed this behavior. This behavior can be explained by the magnetic properties of these alloys. All the paramagnetic alloys have $dE/dT < 0$ and all the ferromagnetic alloys have $dE/dT > 0$ except alloy no. 15 where $dE/dT \simeq 0$. Fine and Ellis (44,45) have shown that the Young's modulus of paramagnetic materials always have $dE/dT < 0$; whereas, alloys in the ferromagnetic state show a minimum in the Young's modulus and dE/dT is positive between this minimum and the Curie temperature (Figure 9). At low temperature, dE/dT is again negative. Evidently the ferromagnetic alloys

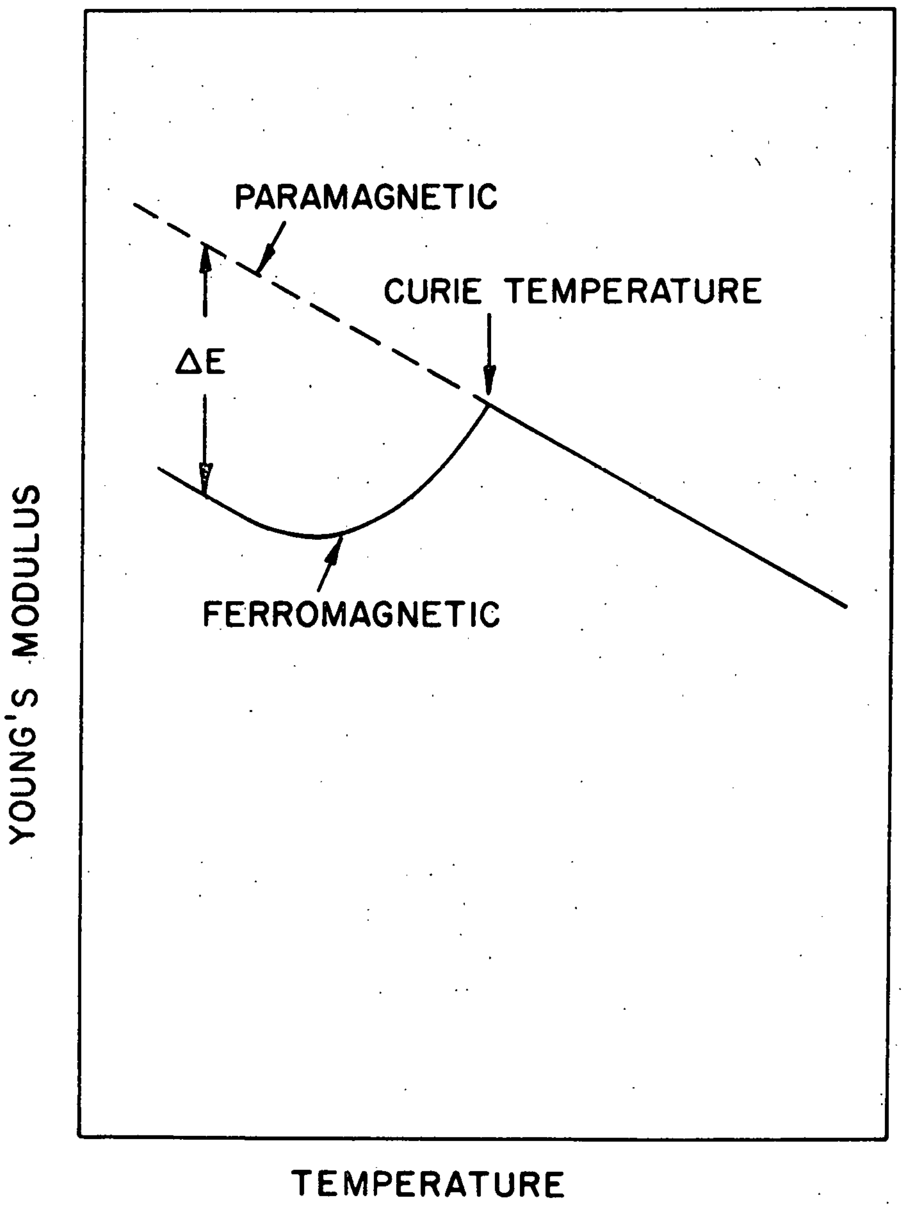

Figure 9. The effect of ferromagnetism on the temperature dependence of Young's modulus (after Fine and Ellis (44,45))

of this investigation were in the temperature range between this minimum and the Curie temperature, thus dE/dT > 0. Alloy no. 15 is very weakly ferromagnetic and its value of dE/dT only shows that the schematic of Fine and Ellis is approximate and may not be followed exactly for border line cases.

The same arguments can be used to explain the temperature dependence of the shear modulus and bulk modulus. Figures 10 and 11 show typical behavior of the shear modulus and bulk modulus respectively.

The quantity C_{12}-C_{44} is considered to be the volume dependent energy term contribution to the bulk modulus (46). Negative values of which usually signify covalent bonding. All the alloys demonstrate a negative value at low temperature except the alloys with low nickel contents which demonstrate a tendency to form "2,2,5" martensite. The significance of this is not known.

Elastic Anisotropy

The elastic anisotropy is defined as the ratio of the two elastic shear constants, $2C_{44}/(C_{11}-C_{12})$. In no alloy did the anisotropy become large as the M_s was approached as discussed in the introduction. The values obtained for all of the alloys varied only from 3.09 to 4.58. This compared to

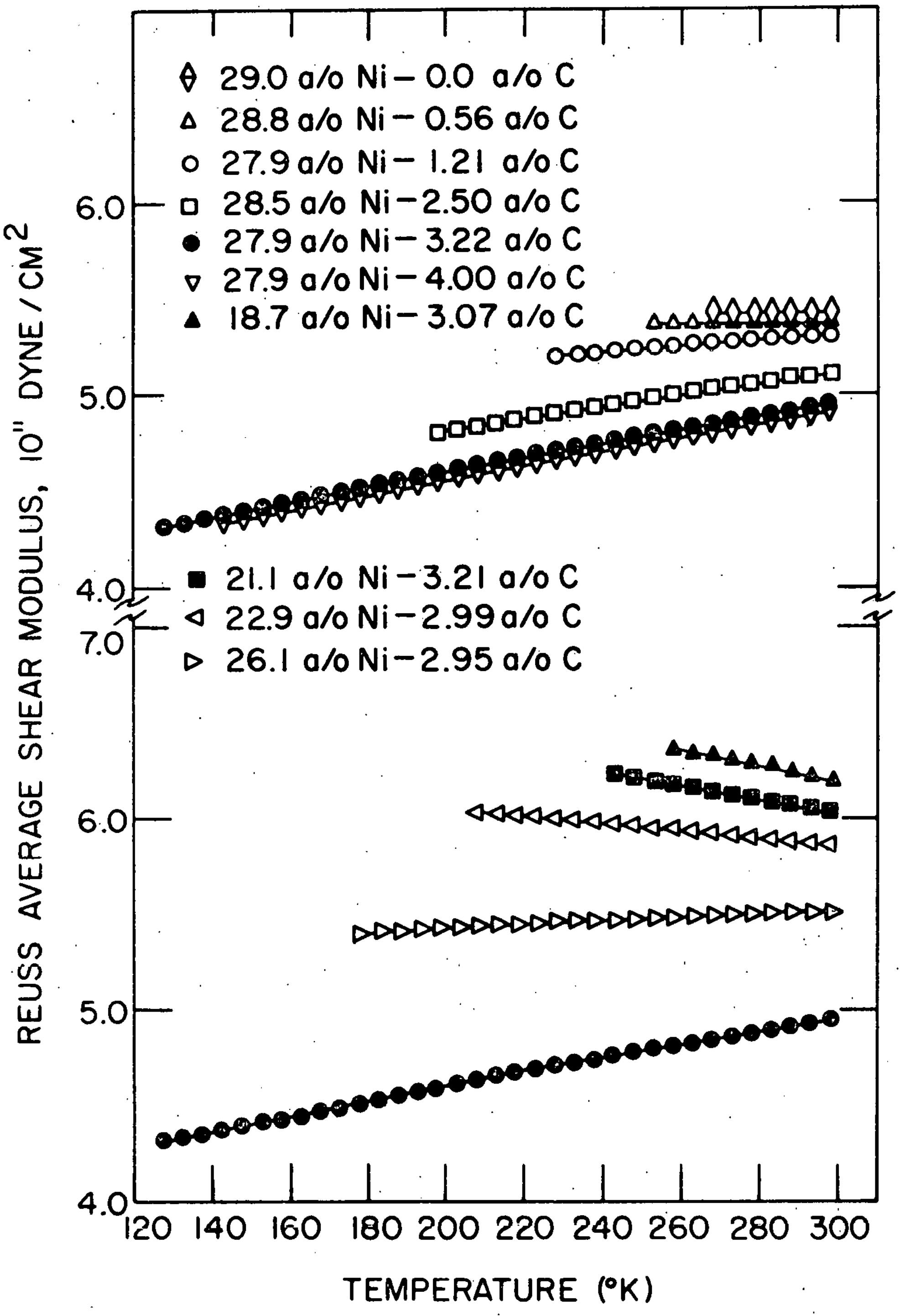

Figure 10. The effect of nickel and carbon on the temperature dependence of the Reuss average shear modulus

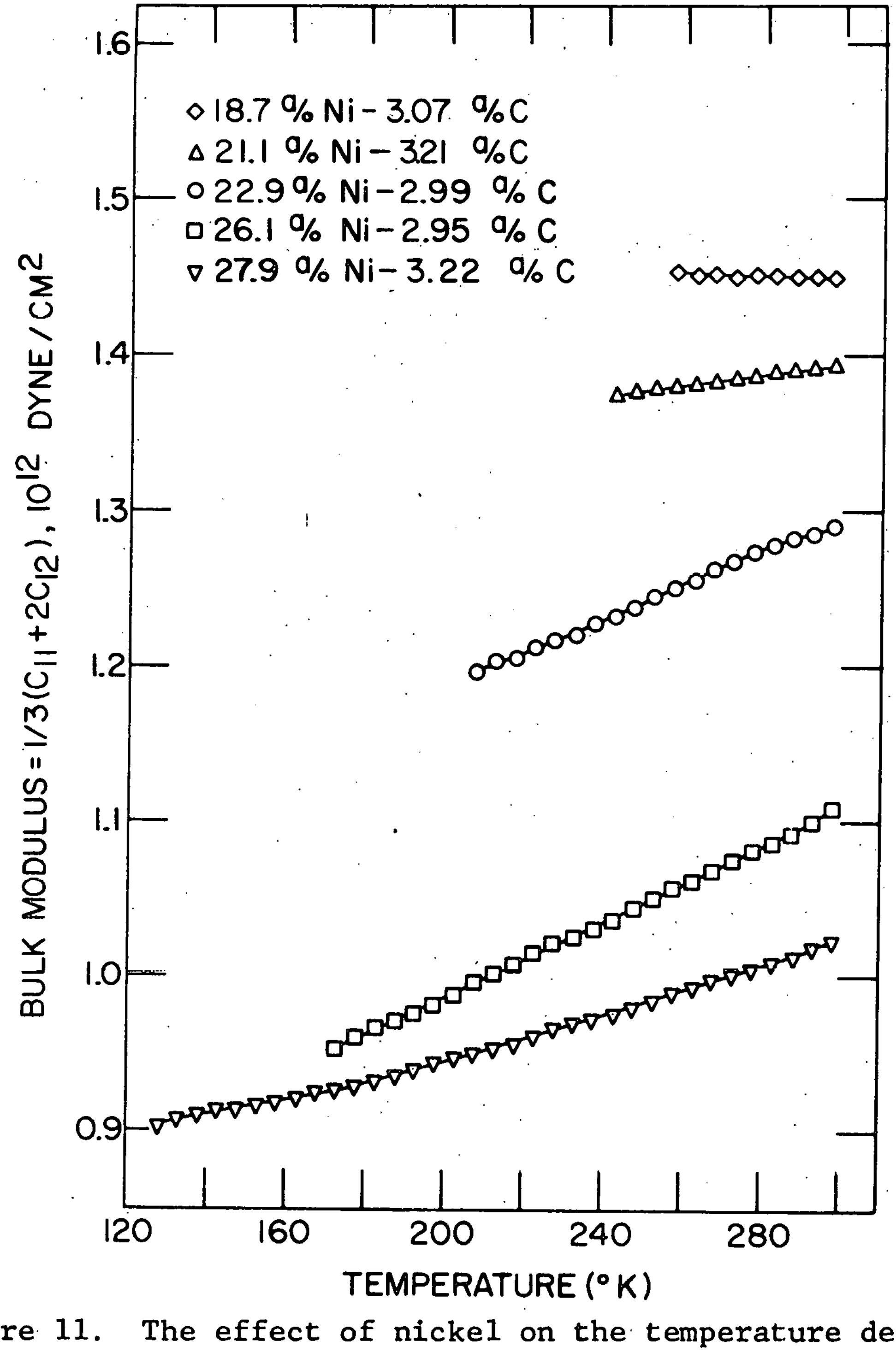

Figure 11. The effect of nickel on the temperature dependence of the bulk modulus

values of 3.2 for copper and 3.9 for lead both of which exhibit stable lattices. In most cases the elastic anisotropy did increase as the temperature was lowered but only slightly. For the low nickel alloys, the values actually decreased as the M_s was approached. This small change in elastic anisotropy with temperature agrees with the results of Salma and Alers (22) for an Fe-30 a/o Ni single crystal. Figures 12 and 13 show the compositional and temperature dependence of the elastic anisotropy for typical Fe-Ni-C alloys.

Single Crystalline Elastic Properties

The temperature dependence of the adiabatic elastic constants is given in Table 4. Figures 3 to 5 show the effect of carbon on the 28.5 a/o Ni series of alloys. Figures 6 to 8 show the effect of nickel on alloys containing approximately 3.12 a/o C. The same relative changes in slope are followed by all of the alloys. Both carbon and nickel additions lower C^L, C', and C_{44} except in the 28.5 a/o Ni series where C^L increases slightly when carbon increases from 0 to 0.56 a/o and from 3.22 to 4.00 a/o (Figure 3). This general decrease in elastic constants with the addition of nickel and carbon conflicts with the idea that the shear constants should

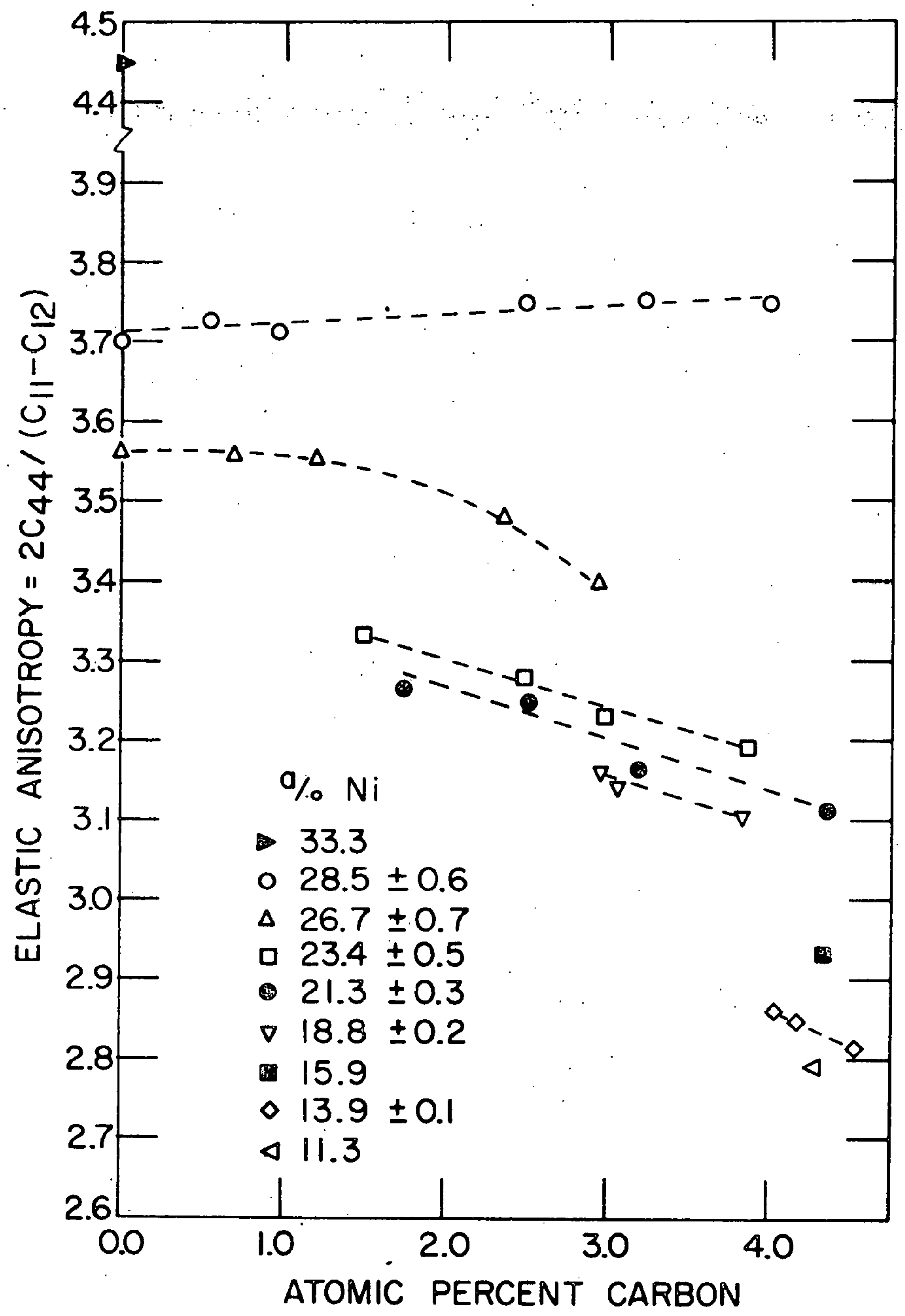

Figure 12. The compositional dependence of elastic anisotropy at 298°K

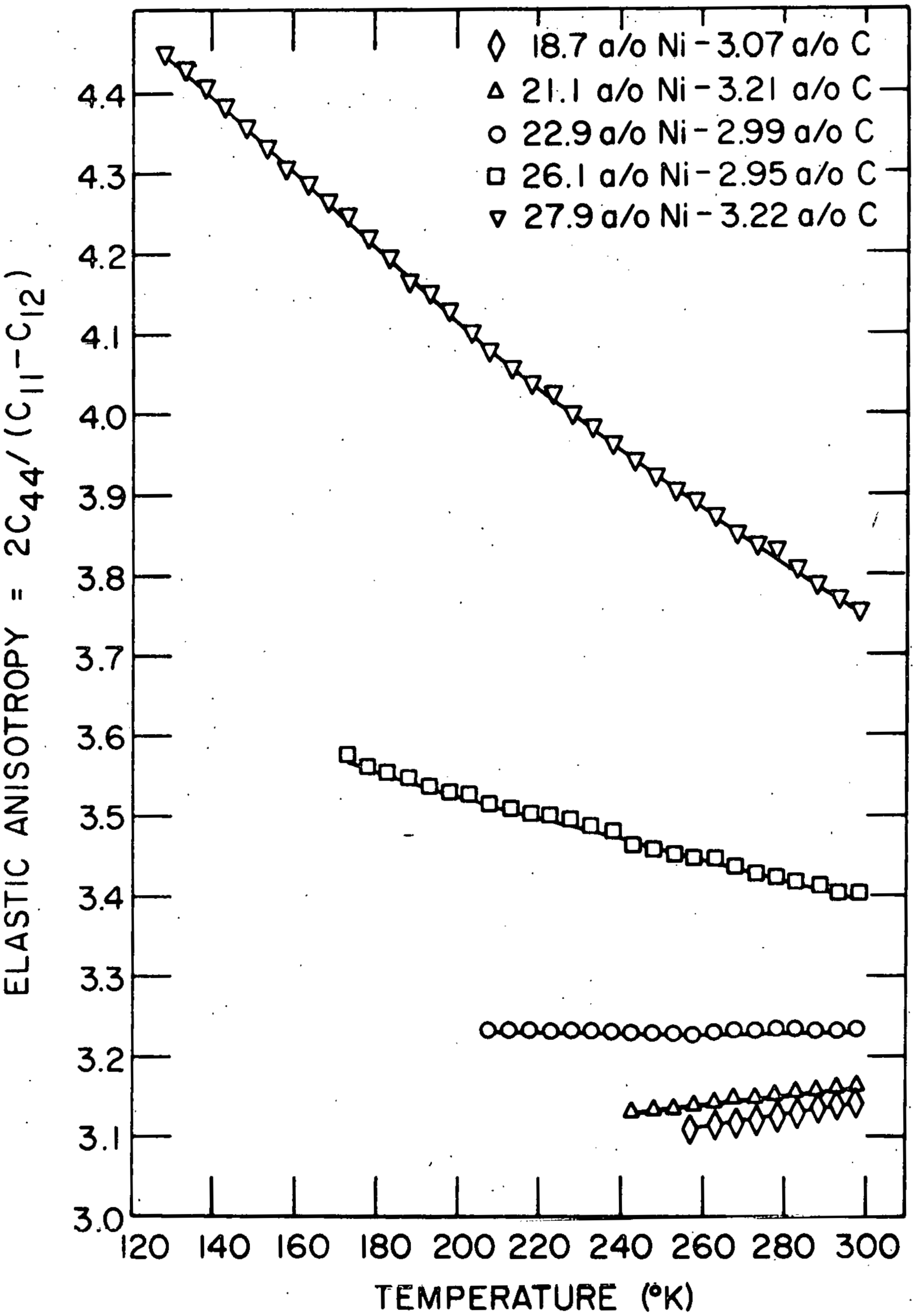

Figure 13. The effect of nickel on the temperature dependence of elastic anisotropy

become small as the M_s is approached as discussed in the introduction. Nickel and carbon both are known to be austenite stabilizers which means the M_s moves further away from room temperature as these elements are added to the alloy. It would then seem reasonable to expect the shear constants to increase in magnitude with the addition of nickel and carbon.

The temperature dependence of the elastic constants in some alloys is observed to support the idea that the shear constants should become smaller as the M_s is approached. However, it is not observed in others. The alloys with high nickel content do have the positive slope expected but the relative change in value of the shear constants are small. The alloys with low nickel concentrations actually have negative slopes.

At this point, a relationship was sought between the elastic constant behavior and the type of martensite each alloy will nucleate. Although the habit plane was only experimentally determined for one alloy, crystal no. 25, it is possible to distinguish the types of martensite by metallographic examination (1,47). Figures 14 and 15 are photomicrographs of what is believed to be predominantly "2,2,5"

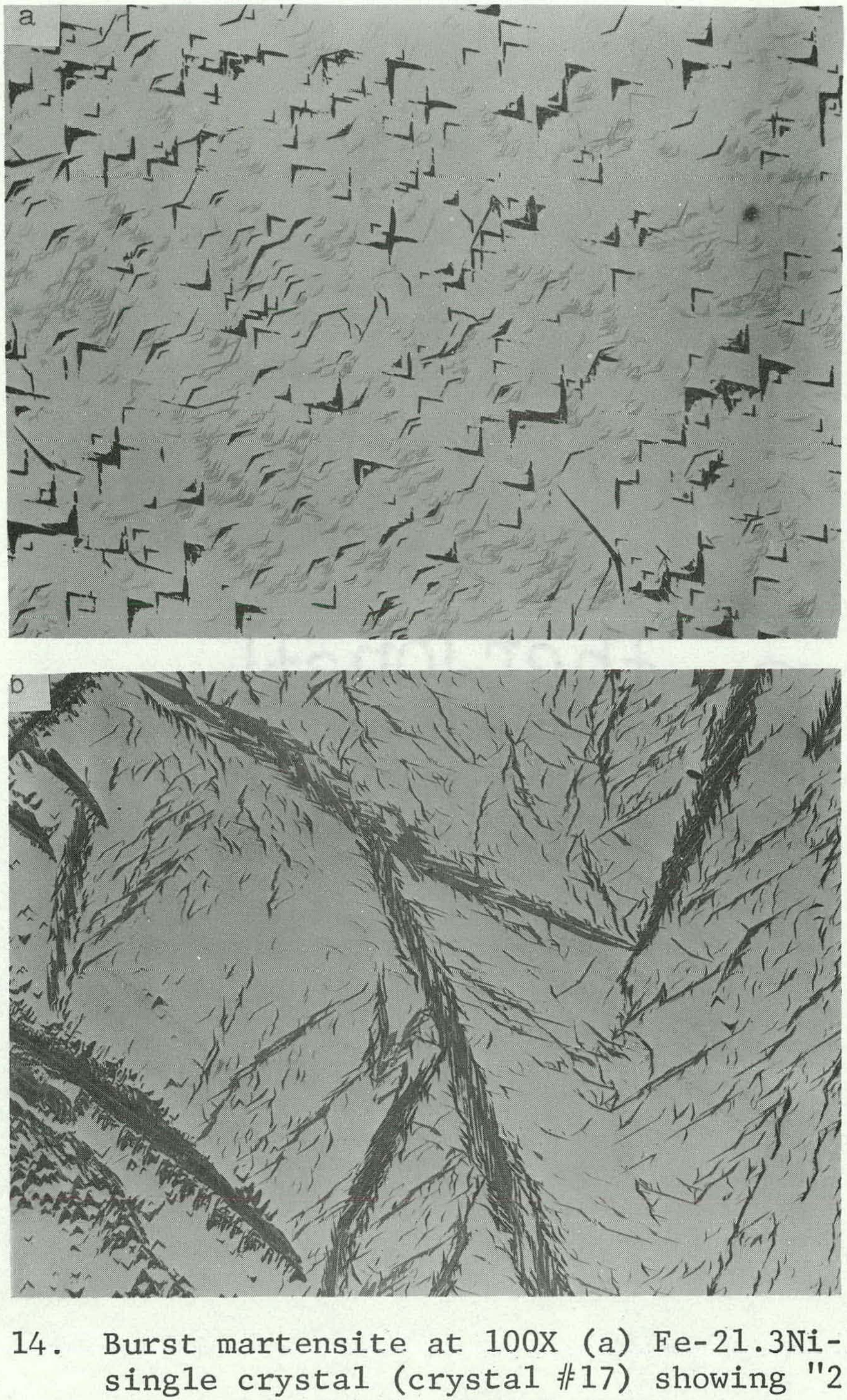

Figure 14. Burst martensite at 100X (a) Fe-21.3Ni-1.76C single crystal (crystal #17) showing "2,2,5" martensite (b) Fe-23.9Ni-2.49C single crystal (crystal #13) showing "2,2,5" and "2,5,9" martensite

Figure 15. Burst martensite with "2,2,5" habit plane in Fe-12.2Ni-4.29C single crystal (crystal #28) at 100X

martensite and Figure 16 is a photomicrograph of "2,5,9" martensite. Table 6 lists the habit plane each alloy is believed to have on the basis of metallographic examination. Also included are the signs of the temperature derivatives of C^L, C', and C_{44} for the crystals in which a temperature dependence was measured. It can be seen that if all the elastic constants have negative slopes, "2,2,5" martensite is always present. Also if $dC^L/dT > 0$, "2,5,9" martensite is present. The temperature dependence of either shear modulus seems to have no effect on the nucleation and growth of "2,5,9" martensite which is very surprising since martensite is known to have predominantly a shear mechanism of formation.

Since the elastic constants have not been reported at the actual M_s, one could argue that the values may change drastically at the M_s. However, on several occasions various elastic constants were accidentally measured at temperatures down to the M_s and no unusual behavior was observed. At the onset of transformation the transducer bonds failed. This prevented an examination of the temperature dependence of the elastic constants at temperatures below M_s.

The criteria observed for the formation of "2,5,9" martensite is a sufficient but not a necessary condition.

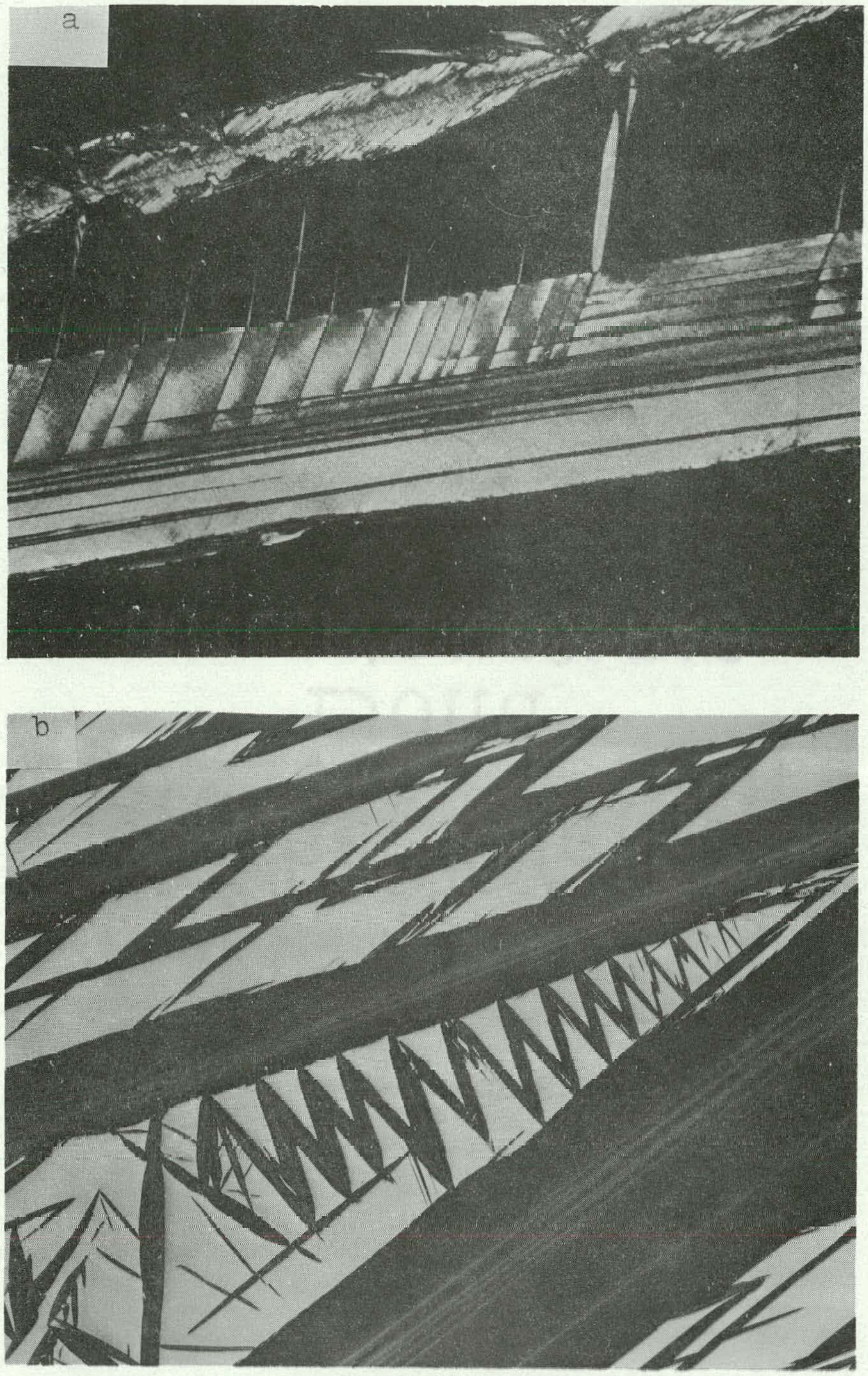

Figure 16. Burst martensite with "2,5,9" habit plane in Fe-26.3Ni-2.36C single crystal (crystal #11) showing midrib and twinned structure; (a) 500X polarized light (b) 150X bright light

Table 6. Observed martensite morphology and sign of $\Delta C/\Delta T$ of Fe-Ni-C alloys

Crystal	Habit plane			Sign of $\Delta C/\Delta T$		
	"111"	"259"	"225"	C^L	C'	C_{44}
1[a]				+	+	+
2	x			+	+	-
3		x		+	+	-
4		x		+	+	-
5		x		+	+	+
6[a]				+	+	+
7[a]				+	+	+
8	x			+	+	-
9		x	x	+	-	-
10		x		+	-	-
11		x		+	+	-
12		x		+	+	-
13		x	x	0	-	+
14		x		+	-	-
15		x		+	-	-
16[a]				+	-	-
17			x	0	-	-
18		x	x	-	-	-
19		x		0	-	-
20				-	-	-
21		x	x	-	-	-
22		x	x	-	-	-
23		x	x	-	-	-
24			x	-	-	-
25			x	-	-	-
26			x	-	-	-
27			x	-	-	-
28			x	-	-	-

[a] Martensite not observed.

There are alloys which have the "2,2,5" criteria and exhibit both "2,2,5" and "2,5,9" martensite (Figure 14b). It is entirely conceivable that there is a broad area in composition where alloys can have both "2,2,5" and "2,5,9" martensite. As one type of martensite plate nucleates and grows, the stresses induced in the austenite by the growing martensite plate may be just sufficient to nucleate the other type of martensite.

The "1,1,1" type martensite forms in alloys which contain no carbon. The elastic constants show the same behavior as those for "2,5,9" martensite with the additional restriction that $dC_{44}/dT < 0$. There are other alloys which demonstrate this elastic constant behavior and yet "2,5,9" martensite results because carbon was present. Carbon must prevent the "1,1,1" martensite mechanism from operating. Further cooling finally forces the "2,5,9" mechanism to operate. This behavior is also observable in the M_s measurements for these alloys. The single crystal M_s values for the 28.5 a/o Ni series given in Table 3 are plotted in Figure 17. The linear extrapolation of these values indicates a much smaller value for the M_s of an alloy containing no carbon. This value is indeed the M_s if the martensite were to form as

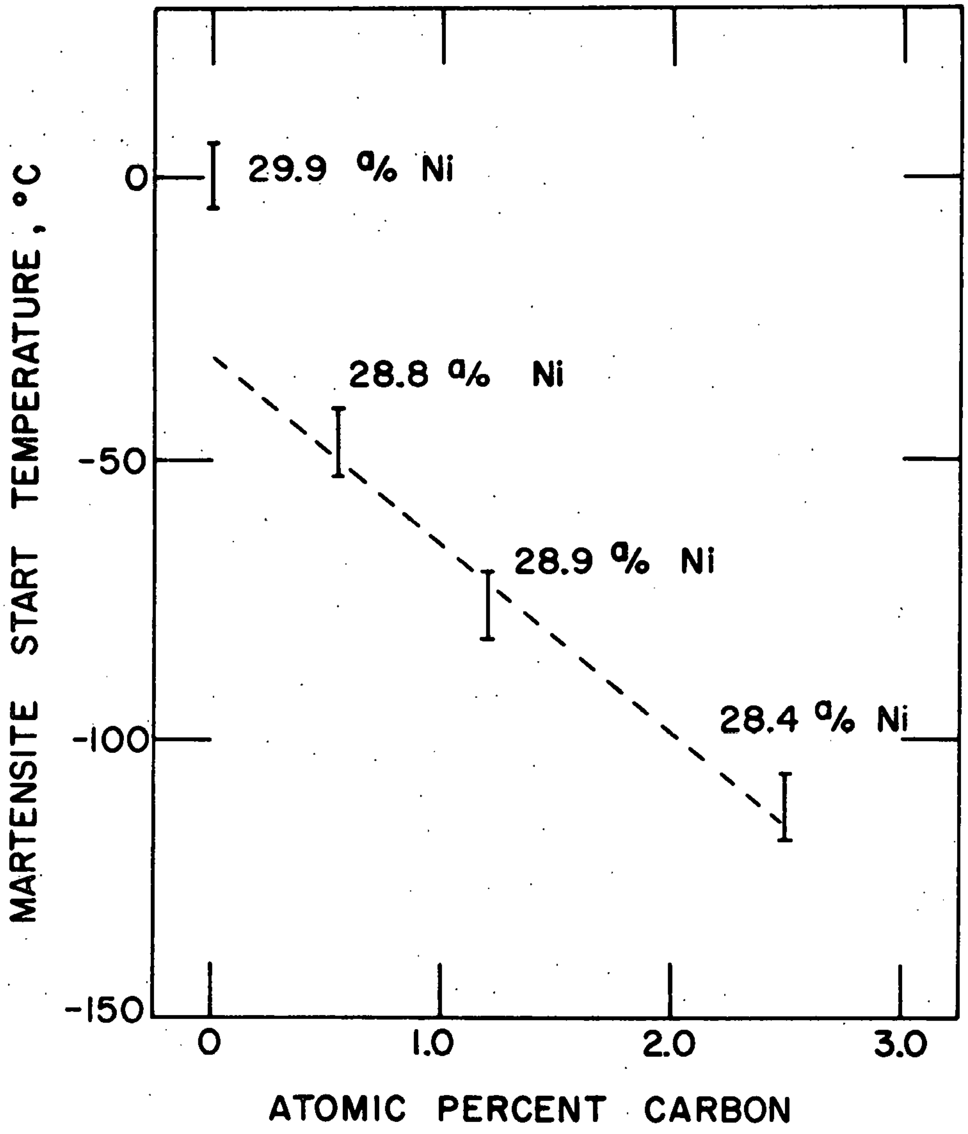

Figure 17. The effect of carbon on the single crystal M_s for alloys containing similar amounts of nickel

"2,5,9" martensite. Since there is no carbon present the "1,1,1" mechanism has already operated and martensite was formed at a higher temperature.

"1,1,1" type martensite has been observed in alloys containing carbon (48,49). However, the M_s of each alloy was between 100 and 500^{o}C. The thermal energy present at these temperatures must be sufficient to activate the "1,1,1" mechanism over the carbon barrier.

Whatever is the critical factor controlling the nucleation of martensite, it has not been identified by the single crystal adiabatic elastic constants of the austenite. General trends have been observed, but it is believed that martensite nucleation is controlled by many parameters, the elastic constants being just one. However, it must be remembered that these measurements have been made using long wavelength phonons ($\lambda \sim 0.05$ cm) and it may be that at very short wavelength phonons the shear constants do indeed approach zero as the temperature is lowered.

Debye Temperatures

The Debye temperatures of crystals 1 through 28 were calculated at every 25^{o}C and are included in Table 5. Most of the significance of Debye temperature is lost if not calculated from 0^{o}K measurements. However, for reasons of comparison the Debye temperatures have been calculated by the method of DeLaunay (46) for the alloys of this investigation and also from the elastic constants given in literature for related systems. A value of 405.4^{o}K was calculated for crystal no. 2 which corresponds to a value of 400.4^{o}K calculated from the elastic constant results of Alers *et al*. (43). However, the nickel compositions differ by one atom percent. Table 7 lists the elastic constant results reported for alloys related to those used in the present investigation. The Debye temperatures have been calculated using these results and are also included.

Recently (50) the Debye temperatures of a series of face-centered cubic Fe-Ni alloys were calculated using measured values of the Young's modulus and the shear modulus. These Debye temperatures are usually 2-3% higher than those determined from elastic constant data. These results are shown in Figure 18 for both the ferromagnetic and paramagnetic states. It can be seen that there is a minimum at about 40% Ni. Unfortunately it is not known if this is in atom percent or weight percent, although the difference for Fe-Ni alloys is small. These results agree with the general concentration

Table 7. Elastic constants and Debye temperatures of Fe, Ni and Fe-Ni alloys

Material	C_{11}	C_{12}	C_{44}	θ_D (^oK)	Temp. (^oK)	Ref.
Fe-30 a/o Ni	1.463	0.881	1.132	400.4	293	43
Fe-29 a/o Ni	1.526	0.916	1.131	405.4	298	present
Ni	2.612	1.508	1.317	476.6	0	43
	2.508	1.500	1.235	460.4	300	
Ni	2.528	1.52	1.238	459.8	300	51
Ni	2.504	1.526	1.254	458.3	300	52
Fe(bcc)	2.42	1.37	1.215	478	77	53
	2.33	1.35	1.18	467	300	
Fe(bcc)	2.36	1.34	1.19	472	77	54
	2.38	1.32	1.165	463	300	
Fe(fcc) para	2.760	1.735	1.363	484.4	298	present
Upper limit	2.984	1.866	1.413	499.4	298	"
Lower limit	2.576	1.626	1.270	467.1	298	"
Fe(fcc) ferro	3.727	0.701	1.622	632.6	298	"

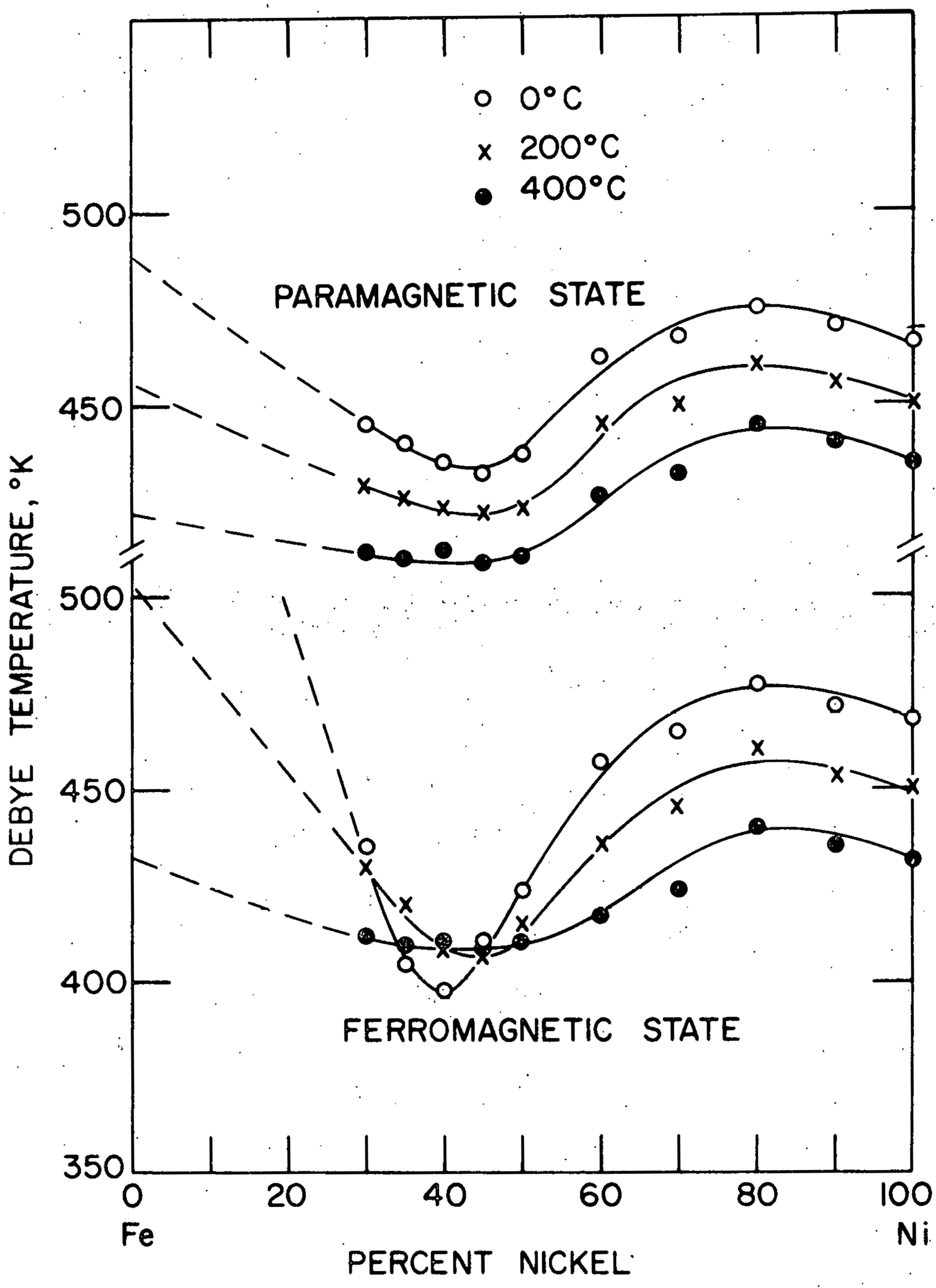

Figure 18. The Debye temperature for Fe-Ni (fcc) alloys at 0°, 200° and $400^{\circ}C$

dependence observed by Bower et al. (55). However, the latter author failed to attribute any significance to his two lowest nickel concentration alloys which do indicate the presence of a minimum. Bower did not have enough data points to really say there was a minimum in Debye temperature at about 40 a/o Ni.

In the present investigation all the alloys which are paramagnetic at room temperature always show an increase in Debye temperature as the temperature is decreased (Table 5). Figure 18 shows that the alloys in the paramagnetic condition have the same behavior. However, it can be seen that the ferromagnetic alloys may have any behavior depending on how far the compositions are away from the minimum. Of course the location of the minimum is not the same for Fe-Ni-C alloys as it is for Fe-Ni alloys. The alloys which are not marked "ferro" or "para" in Table 5 are ferromagnetic but this is because ferromagnetic martensite is present in these alloys at room temperature. From the behavior of the Debye temperatures, the austenite phase in crystal no. 8 is probably ferromagnetic and all the other unmarked alloys are probably paramagnetic. This is consistent with the condition of the alloys surrounding these particular crystals.

Properties of Face-Centered Cubic Iron at Room Temperature

From Figures 19 to 21 it was possible to estimate the elastic constants of pure face-centered cubic iron at room temperature. The alloys were divided into groups which best approximated isoconcentrations of nickel. Each set of data was then fit to a linear least squares solution with dependence on nickel and carbon. This was done for the approximate nickel isoconcentrations of 28.5, 26.7, 23.4, and 21.3 a/o. There were not enough data points for alloys with less nickel concentrations. Therefore the alloys with 21.3 a/o Ni were combined with the alloys with the 18.8 a/o Ni group and the slope determined from these alloys was used for all the remaining nickel concentrations. Extrapolating all these straight lines to zero percent carbon gave values which could then be plotted against nickel concentration. Figures 22 to 24 are these plots and they clearly show the effect of ferromagnetism on elastic constants. A linear least squares fit was then applied to both the paramagnetic and the ferromagnetic portions and extrapolated to pure iron. The results for the elastic constants obtained in this manner are given in Table 7. Also included in Table 7 are the values obtained for the pure iron elastic constants by applying all the data

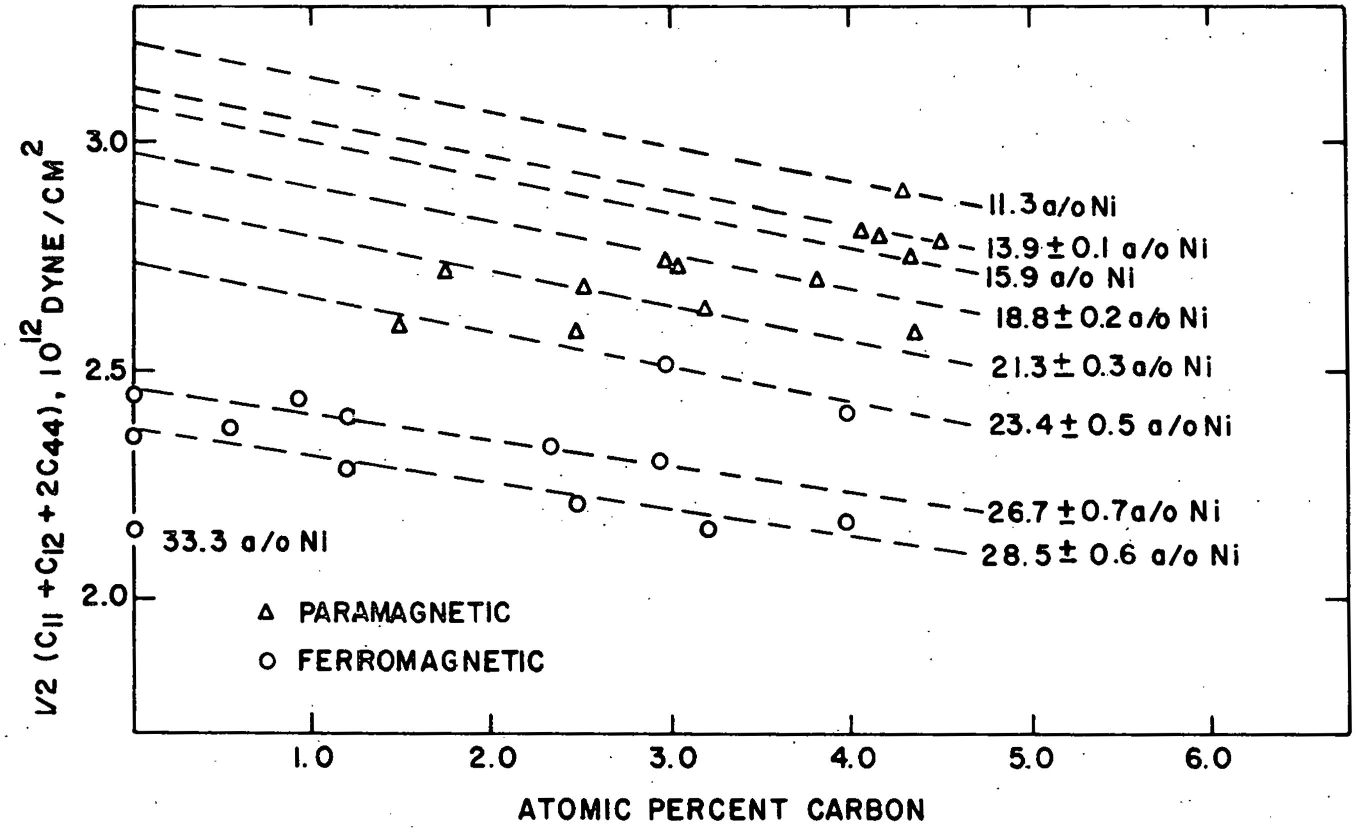

Figure 19. The compositional dependence of C^L at 298°K used to extrapolate the values for Fe-Ni alloys

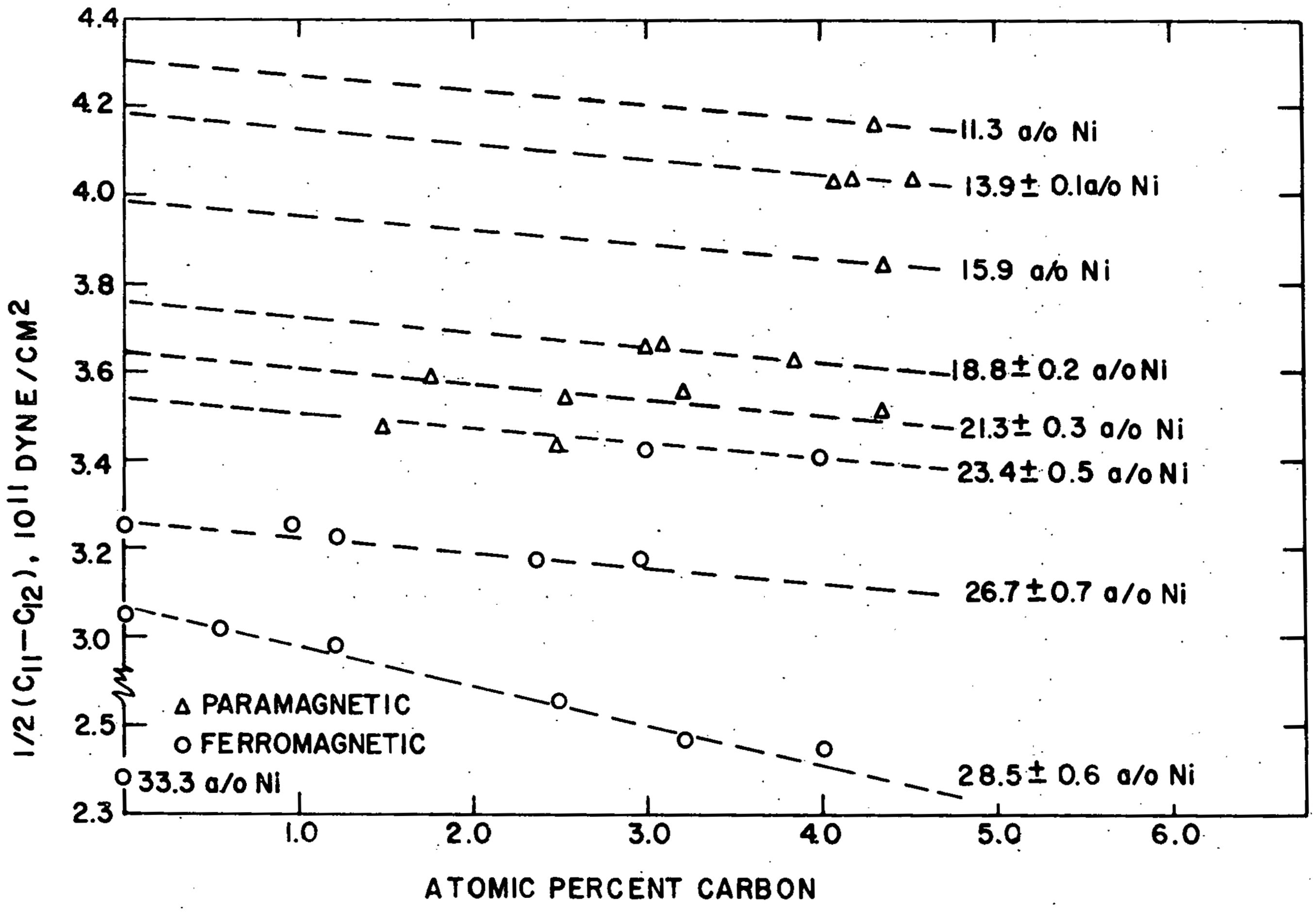

Figure 20. The compositional dependence of C' at 298°K used to extrapolate the values for Fe-Ni alloys

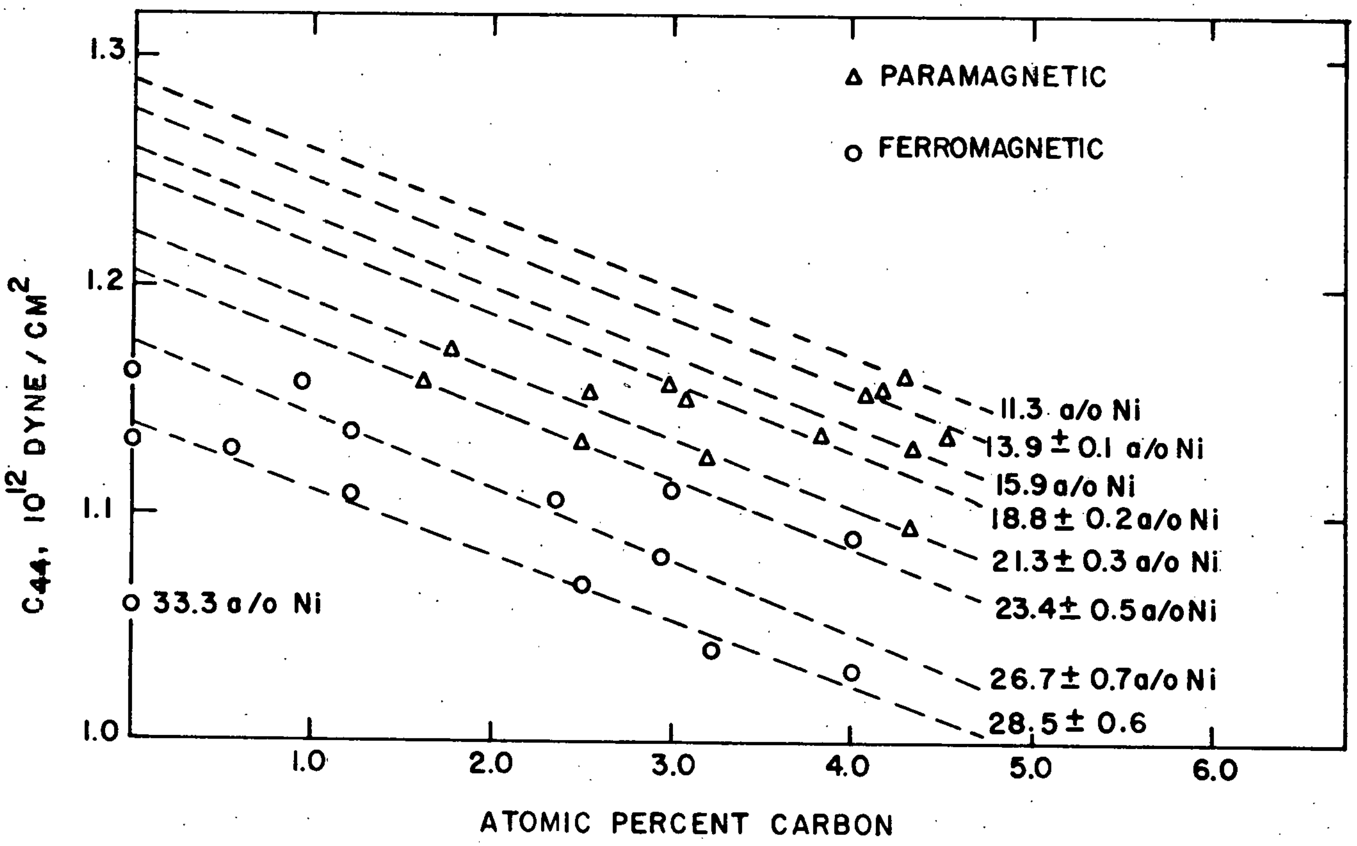

Figure 21. The compositional dependence of C_{44} at 298°K used to extrapolate the values for Fe-Ni alloys

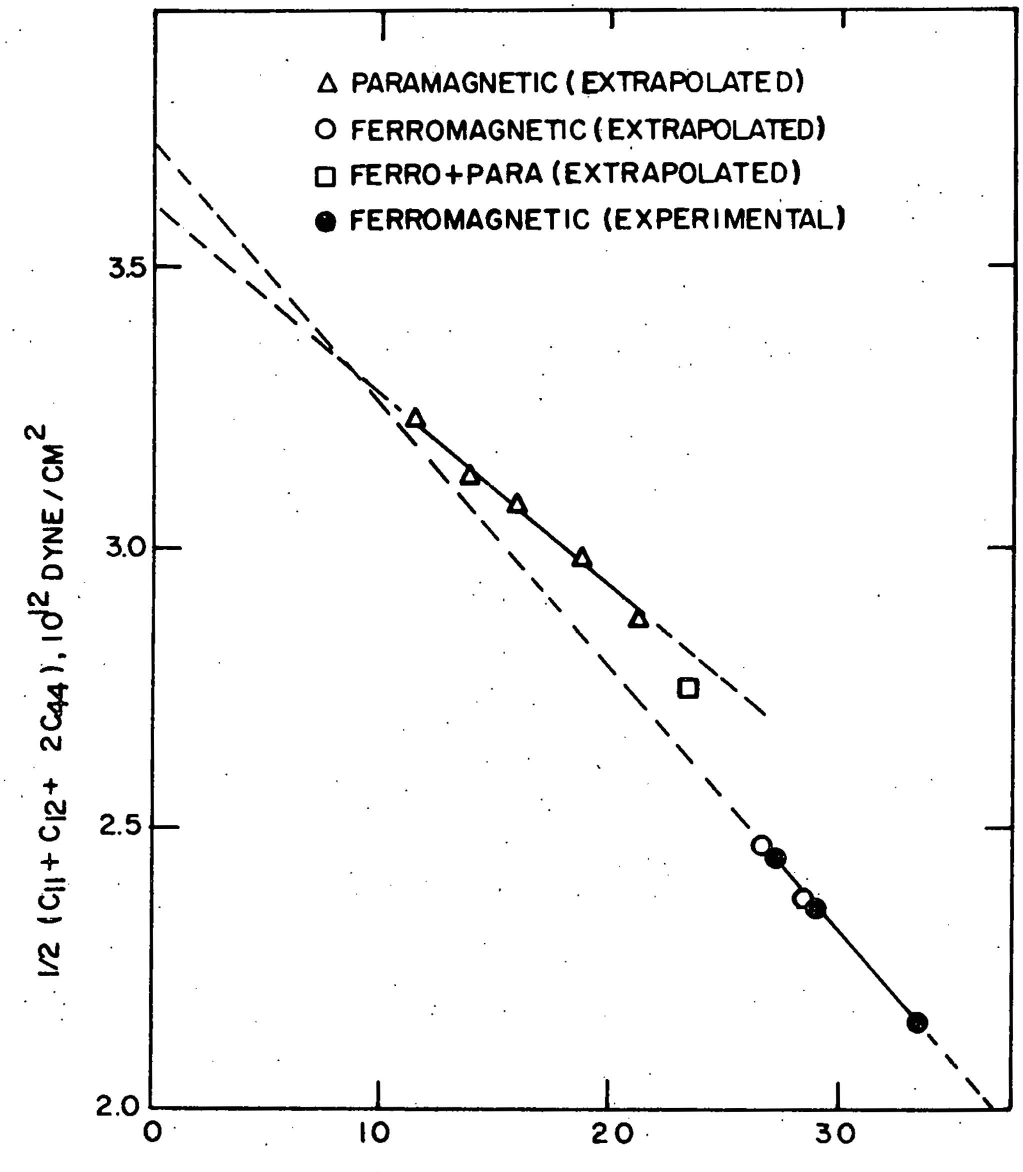

Figure 22. The extrapolation of C^L to pure iron in the paramagnetic and ferromagnetic state

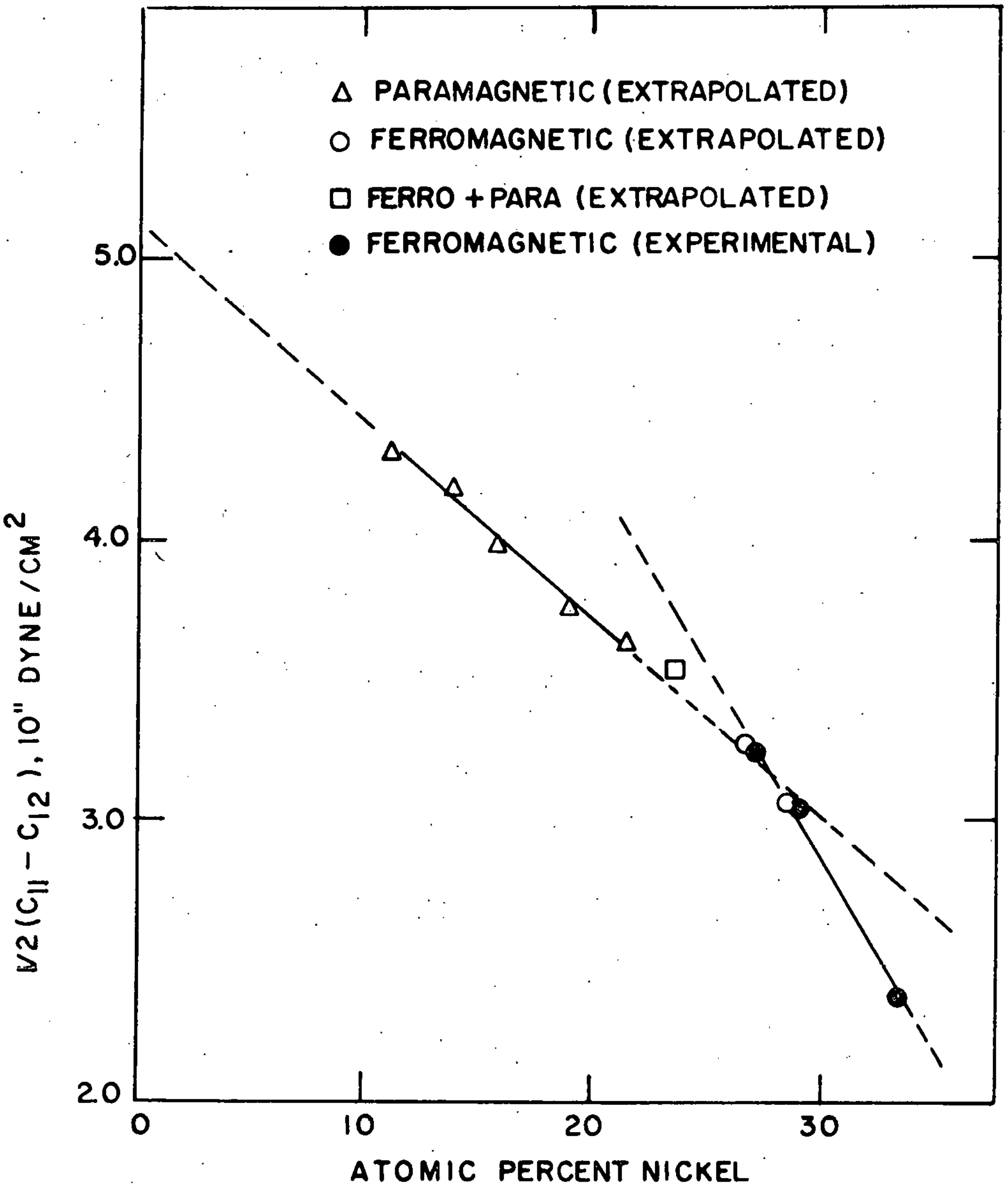

Figure 23. The extrapolation of C' to pure iron in the paramagnetic and ferromagnetic state

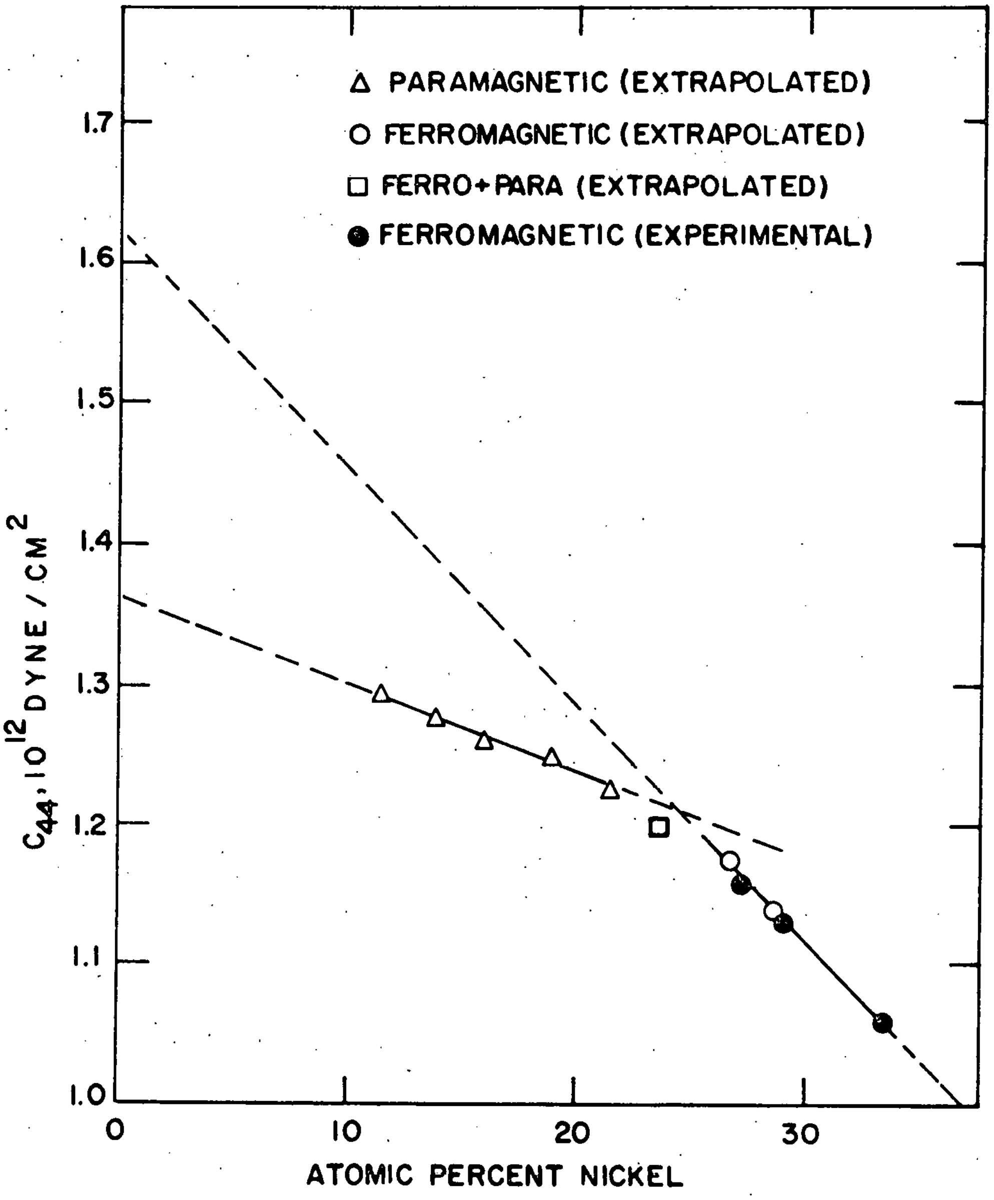

Figure 24. The extrapolation of C_{44} to pure iron in the paramagnetic and ferromagnetic state

simultaneously to a least squares fit to the following two functions:

$$C_{ij} = B(1) + B(2)Ni + B(3)C \tag{17}$$

$$C_{ij} = B(1) + B(2)Ni + B(3)C + B(4)Ni^2 \tag{18}$$

Many other expressions were tested but these two seem to fit the data best ($\pm$ 8%). The reason these results are included is to give an idea of the accuracy of the extrapolation procedure first described. It can be seen that expression 17 and 18 seem to give upper and lower limits to the extrapolated values.

The Debye temperatures of face-centered cubic iron calculated from these extrapolated elastic constants by the method of DeLaunay (46) are also included in Table 7. Extrapolating to pure iron on Figure 18 yields values at 490°K at 0°C and 456°K at 200°C for the face-centered cubic paramagnetic state. Interpolating between these values yields a value of 486°K at room temperature. This is in excellent agreement with 484.4°K obtained from the extrapolated elastic constants. Similarly, the ferromagnetic state shown in Figure 18 gives a value of 622°K at 25°C which again is in excellent agreement with the value of 632.6°K obtained from extrapolated elastic constant data from the face-centered cubic ferromagnetic alloys. These Debye temperatures are higher than the 432°K value assumed for face-centered cubic iron by Blackburn *et al*. (56). It should be stressed again that the present investigation Debye temperatures were obtained from room temperature data and may well be different at 0°K. However, the temperature dependence as shown in Figure 18 indicates that the Debye temperature at 0°K would be larger than the value at room temperature.

SUMMARY

The single crystalline elastic constants have been measured for a series of face-centered cubic Fe-Ni-C alloys in the temperature range $M_s \overset{\sim}{+} 10^{o}C$ to room temperature. Polycrystalline elastic properties were calculated from the elastic constants; however, no correlation was observed between these polycrystalline properties and the observed martensite morphology.

Certain relationships were observed to exist between the parent single crystalline elastic properties and the product martensite morphology. If $dC^L/dT < 0$, $dC'/dT < 0$, and $dC_{44}/dT < 0$, "2,2,5" martensite was observed to form upon transformation. If $dC^L/dT > 0$, either "2,5,9" or "1,1,1" martensite was observed to nucleate and grow. The temperature dependence of either shear constant did not appear to influence the "2,5,9" transformation mechanism. However, if $dC_{44}/dT < 0$ and the alloy had no carbon, an alloy which ordinarily would form "2,5,9" martensite would form "1,1,1" martensite instead. It was postulated that the "1,1,1" martensite transformation mechanism required less energy to operate than the "2,5,9" martensite mechanism if the alloy contained no carbon. The carbon must prevent the "1,1,1" mechanism from operating below room temperature and therefore allows the "2,5,9" mechanism to operate upon further cooling.

Both "2,2,5" and "2,5,9" martensite can be present in the same alloy. It is believed that if $dC^L/dT \simeq 0$ and if $dC'/dT < 0$, the growth of one type of martensite can nucleate the other type of martensite.

It has been concluded from the above observations that the properties of the parent austenite do indeed effect the product martensite morphology. There appear to be many parameters effecting the nucleation and growth of martensite and the elastic constants of the parent phase are just a few. The value of dC^L/dT of the parent phase appears to have the most influence on the resultant habit plane. This must be involved through the volume expansion of the martensite during growth. If $dC^L/dT > 0$, the parent phase can accommodate the expansion of the martensite more easily as the temperature is lowered.

The magnetic transition from ferromagnetism to paramagnetism present in these alloys does not appear to effect the martensite morphology significantly. Although the transition does coincide with the boundary which separates alloys which form "2,2,5" from those which form "2,5,9" martensite in many alloys, there are enough exceptions to this observation to conclude that the boundary is a result of the elastic constant behavior and not the magnetic transition.

The elastic anisotropy was not observed to increase rapidly as the M_s was approached. In some alloys the value actually decreased. High elastic anisotropy must therefore only establish a sufficient and not a necessary condition for lattice instability.

The compositional dependence of elastic constants has been used to estimate the values of the elastic constants for the face-centered cubic allotrope of pure iron at room temperature. The elastic constants of paramagnetic, face-centered cubic iron based on the compositional extrapolation are $C_{11} = 2.760 \times 10^{12}$ dynes/cm^2, $C_{12} = 1.735 \times 10^{12}$ dynes/cm^2 and $C_{44} = 1.363 \times 10^{12}$ dynes/cm^2. These elastic constants give face-centered cubic iron a Debye temperature of 484.4°K.

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APPENDIX A: HYDROSTATIC DENSITY DATA

The density of each alloy was determined by hydrostatic methods in a bath of diethyl phthalate. The following is a comparison of these results to the theoretical densities.

	Density (gm/cm^3)	
Crystal	Hydrostatic	Theoretical
1	8.1499	8.1879
2	8.1789	8.1903
3	8.1733	8.1749
4	8.1486	8.1513
5	8.1165	8.1369
6	8.0436	8.1258
7	7.9955	8.1262
8	8.1675	8.1950
9	8.1623	8.1744
10	8.1544	8.1633
11	8.1053	8.1361
12	8.0798	8.1283
13	8.1054	8.1592
14	8.1259	8.1366
15	8.0854	8.1227
16	8.0144	8.1096
17	8.0971	8.1569
18	8.1156	8.1192
19	8.0846	8.1079
20	8.0344	8.0995
21	8.0997	8.1043
22	8.0885	8.0957
23	8.0341	8.0946
24	8.0397	8.0748
25	7.9793	8.0680
26	8.0409	8.0761
27	8.0224	8.0703
28	8.0069	8.0578

APPENDIX B: ERROR INTRODUCED BY THERMAL EXPANSION

Since elastic constant data for Fe-Ni-C alloys were investigated in the temperature range $M_S \mp 10^oC$ to 300^oK, it was necessary to estimate the error involved if thermal expansion was neglected. The coefficient of thermal expansion, α, was estimated to be about the same as a low carbon, nickel steel ($\alpha = 10\times10^{-6}/^oC$). For a temperature change of 100^oC,

$$\Delta\ell/\ell = \alpha\Delta T = 0.001$$

$$\Delta V/V = 3\alpha\Delta T = 0.003$$

where ℓ is length and V is volume. Therefore, the density will increase by 0.3% when cooled 100^oC. The transit distance will contract 0.1% which means the wave actually traveled a shorter distance than assumed. Therefore, the true velocity is lower than measured by 0.1%. Since

$$C_{ij} = \rho(v^2)$$

it can be seen that the errors tend to cancel each other. Therefore, the total error involved in the elastic constant calculation is only about 0.1%, i.e.,

$$C_{ij} = (1.003)(.999)^2 = 1.001$$

$$\Delta C_{ij}/C_{ij} = 0.1\%.$$