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Grade 2114: Flexure Strength and Elastic Properties

Timothy D. Burchell

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Material Science and Technology Division

GRADE 2114: FLEXURE STRENGTH AND ELASTIC PROPERTIES

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ABSTRACT

This document reports flexural strength, bulk density, and elastic constants data (the last determined by two separate methods) for Mersen grade 2114, billet 116310. These data are needed to support the design of graphite core components. This technical memorandum is responsive to work package AT-19OR03050405, “Graphite Materials Properties—ORNL.”

1. INTRODUCTION

To fully characterize the within-billet, between-billet, and batch-to-batch variations of a graphite grade it is necessary to section and test several billets. In this document we report the variability of flexural strength of Mersen grade 2114 graphite, billet 116310. Also, we report certain elastic constants, determined from the ultrasonic velocity in the longitudinal and shear wave modes, and the same elastic constants determined from the fundamental frequency (ff) of vibration. Details of the billet cut plan and specimen drawings are reported for information. The tensile and compressive properties of this billet were reported previously.[1]

To test the physical properties data for systematic variations, i.e., σ_f(WG) = σ_f(AG) or σ_f(billet center) = σ_f(billet periphery), we used statistical significance testing[2] or hypothesis testing based upon the unpaired t test[3,4] result. The significance testing levels used are shown in Table 1.

Table 1. Significance levels and their associated P values

P Value	Terminology
Less than 0.0001	Extremely Significant
0.0001 to 0.001	Extremely Significant
0.001 to 0.01	Very Significant
0.01 to 0.05	Significant
Greater than or equal to 0.05	Not significant

The statistical significance of any observed material property difference between location or orientation is determined entirely based on the reported “P” values (a function of the mean and standard deviation), as noted in Table 1. The conventional threshold of P = 0.05 was adopted for hypothesis testing and the null hypothesis was taken as σ_t (1) = σ_t (2). If the derived P value was less than the threshold value, it was reported that the “null hypothesis was rejected” and that the difference was “statistically significant.” However, if the derived P value was greater than the threshold value ($P \geq 0.05$), we reported that the null hypothesis was not rejected and that the difference was “not statistically significant.”

This work has several broad goals:

- To show that this billet has similar density and elastic properties as previously reported[1]
- To show that the measured properties agreed with manufacturers’ literature[5] (when available)
- To determine the isotropy of the graphite
- To determine that the properties are uniform, i.e., billet center same as billet end
- To show the elastic constants are similar regardless of experimental method

2. EXPERIMENTAL

2.1 MATERIALS AND BILLET SECTIONING

All baseline testing reported here was conducted in accordance with the experimental plan.[6]

Mersen grade 2114, billet 116310, was sectioned as shown in the cut plan drawing (Figure 1). The billet was cut into eight typical slabs with slab 1 being the top (end) of the as-molded billet. Each slab was cut into four blocks labeled A, B, C, and D, and each block was further sectioned into four subblocks labeled 1, 2, 3, and 4. To reduce the overall number of specimens, only slabs 1 and 5 were considered for initial testing. Additionally, only subblocks from blocks A and D were sectioned into rectangular specimen blocks from which tensile, compression, and flexure specimens were produced. Typical Mersen grade 2114 properties are given in Table 2.

Table 2. Typical properties of Mersen grade 2114 graphite[5]

Density (g.cm^{-3})	Grain Size (μm)	Porosity (%)	Flexural Strength (MPa)	CTE (10^6/°C)	Resistivity (μ Ω cm)	Thermal Conductivity (W/m°C)
1.81	13	10	52	5.3	1240	104

CTE = Coefficient of thermal expansion.

Mersen 2114 grade is an isostatically molded graphite; the saggars (molds) are vertically oriented when filled such that the effect of gravity before isostatic molding is to align the filler-coke particles with the long axis (in-plane covalent bonds) in the billet transverse direction. The axial orientation of the specimens used here were either parallel to or transverse to the billet long axis such that the specimen orientation to the slight (gravitational) preferred orientation was as follows:

Transverse sample = sample axial direction perpendicular to billet long axis = with grain (WG).

Parallel sample = sample axial direction parallel to billet long axis = against grain (AG).

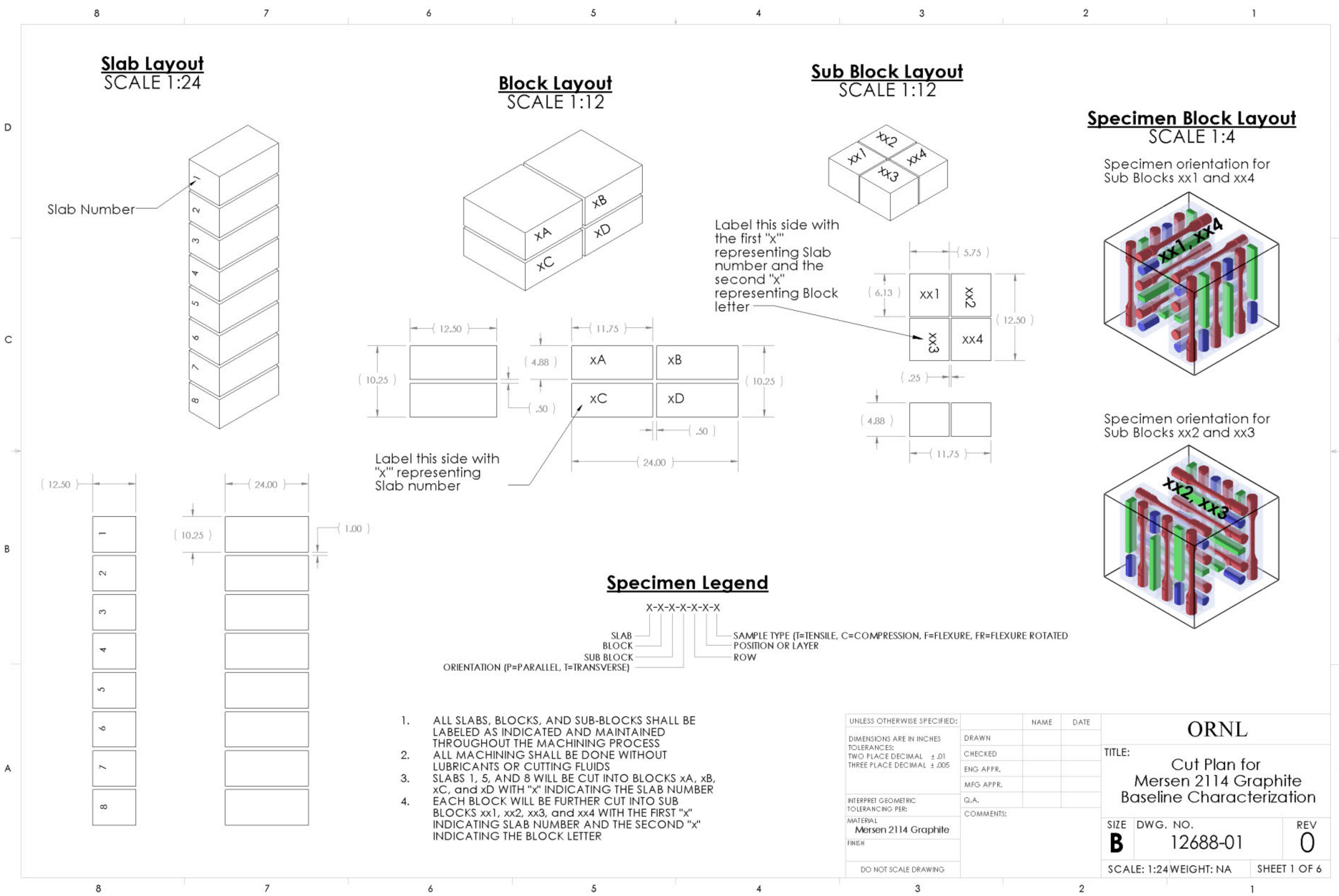


Figure 1. Mersen grade 2114 billet 116310 cut plan (for information only—see experimental plan[6]).

2.2 BULK DENSITY

The bulk density was determined by mensuration using the flexural strength specimens (Figure 2) in accordance with ASTM C559.[7]

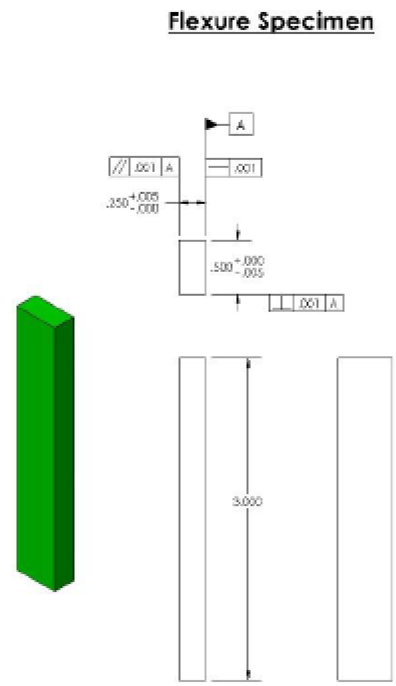


Figure 2. The flexural specimen geometry used (specimen dimensions in inches).

2.3 ELASTIC CONSTANT

2.3.1 Sonic Velocity

The elastic constants, Young's modulus, shear modulus, and Poisson's ratio were determined from the longitudinal and shear wave velocities measured on the compression test specimen.

Figure 3 shows the experimental setup used. ASTM C769[8] was followed for determination of the sonic velocities. Details of the probes used are given in Table 3. The couplants used were Ultragel II, manufactured by SonoTech for the longitudinal wave probes, and Shear Gel, manufactured by SonoTech for the shear wave probes.

The longitudinal velocity was determined as the mean of three consistent time-of-flight (TOF) measurements and shear velocity by two measurements taken 90° apart, each of these also determined as the mean of three consistent TOF measurements. The signal trace was captured by the oscilloscope interface laptop PC. The probes are directly contacting the sample, i.e., there is no stand-off or compliant layer (Figure 4), and therefore there is no zero correction. The TOF measurements and hence ultrasonic velocity are read directly from the laptop PC and are measured between the two moveable cursers, as shown in Figure 5(a). Exact placement of the cursers can be achieved by expanding the initial or final pulse (Figure 5b). Constant probe-specimen pressure is advisable for velocity determinations, especially shear-wave velocity measurements, and was achieved by use of a spring-loaded fixture (Figure 4). The signal trace resulting from probe to probe contact (i.e., no specimen) is shown in Figure 6. The initiating pulse and the transmitted signal are coincident at ~1E-5 seconds, again reinforcing the lack of any zero correction.

A typical ultrasonic longitudinal wave form signal is shown in Figure 7 and a shear wave form signal in Figure 8.

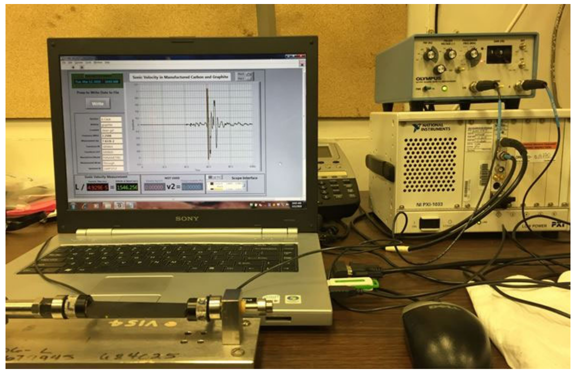


Figure 3. Experimental setup used.

Table 3. Probe frequencies and serial numbers

Manufacturer	Model	Frequency	Serial Number	Wave Type
Panametrics*	V106	2.25 MHz	593888	Longitudinal
Panametrics*	V106	2.25 MHz	593889	Longitudinal
Panametrics*	V154	2.25 MHz	589864	Shear
Panametrics*	V154	2.25 MHz	598869	Shear

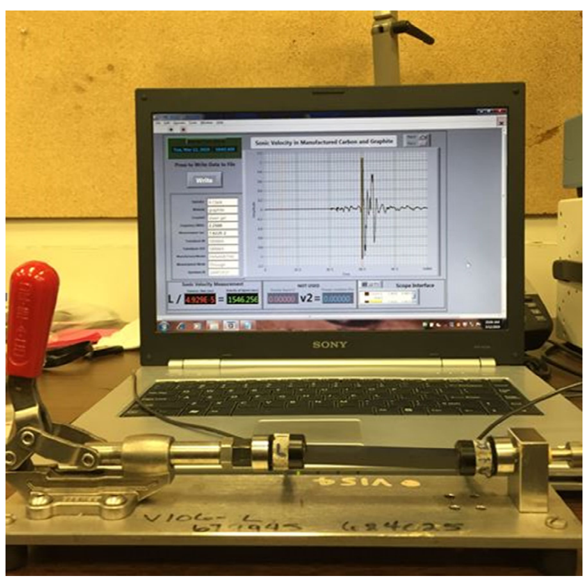
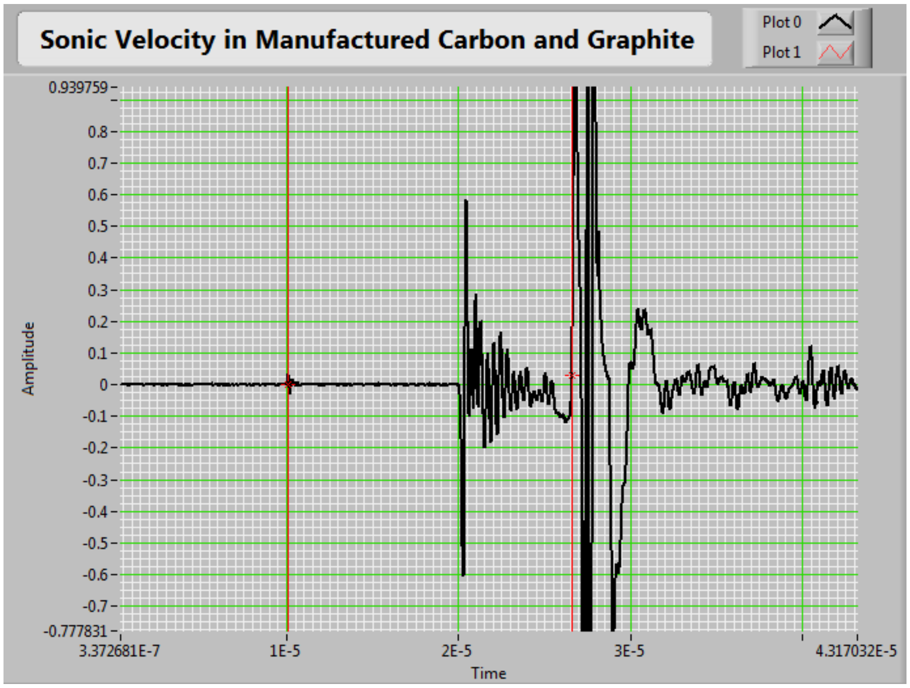
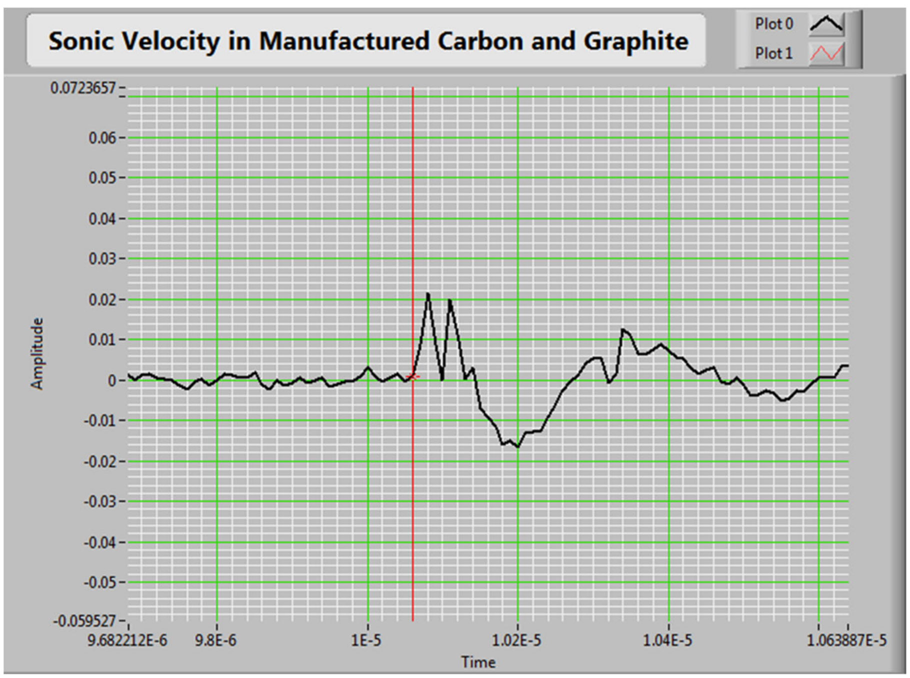


Figure 4. The specimen and probe fixture used. The fixture is spring-loaded to ensure constant probe to specimen contact pressure.



(a)



(b)

Figure 5. Time-of-flight (ultrasonic velocity) measurements: (a) typical ultrasonic signal trace—shear (~ 2.6E-5 s) and longitudinal wave (~2E-5 s), trigger pulse at 1E-5 seconds, and (b) expansion of the initial trigger pulse at 1E-5 seconds.

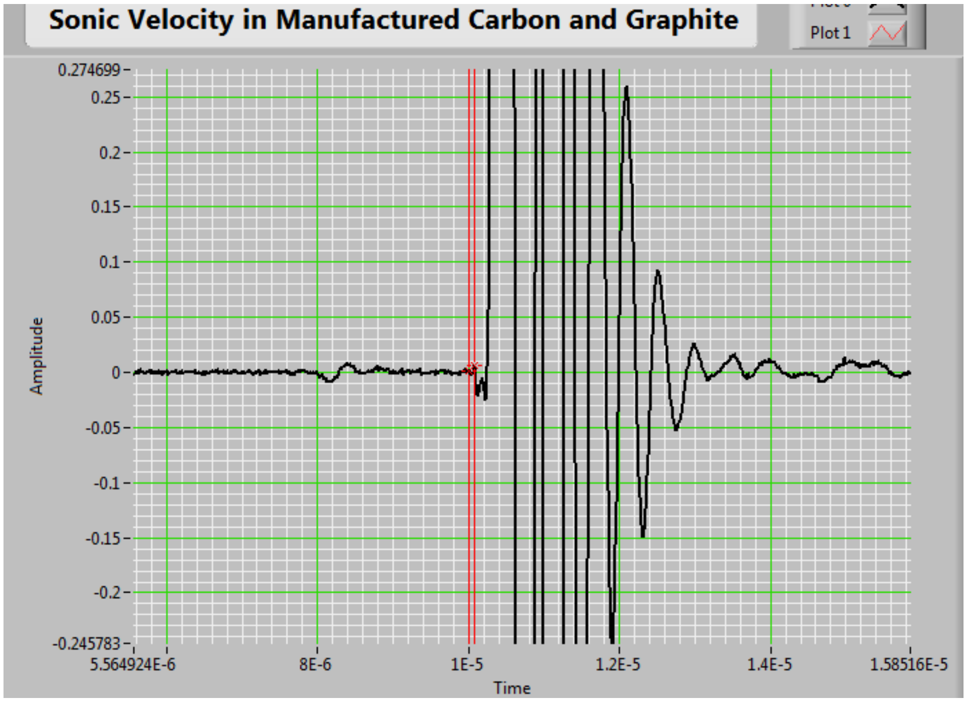


Figure 6. Probe face to probe face contact.

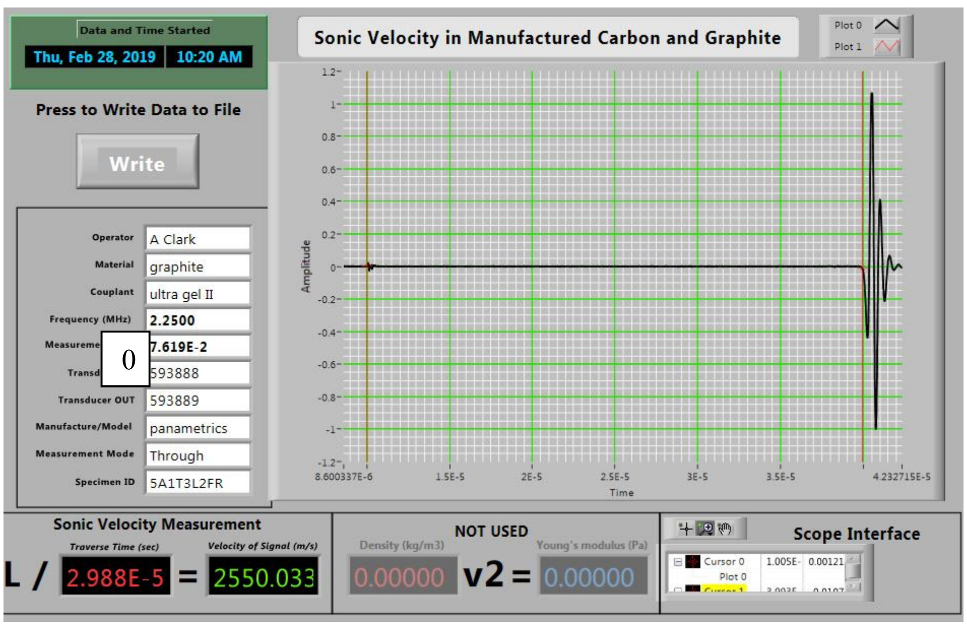


Figure 7. Typical longitudinal wave form (Time-of-flight = 2.988E-5 s).

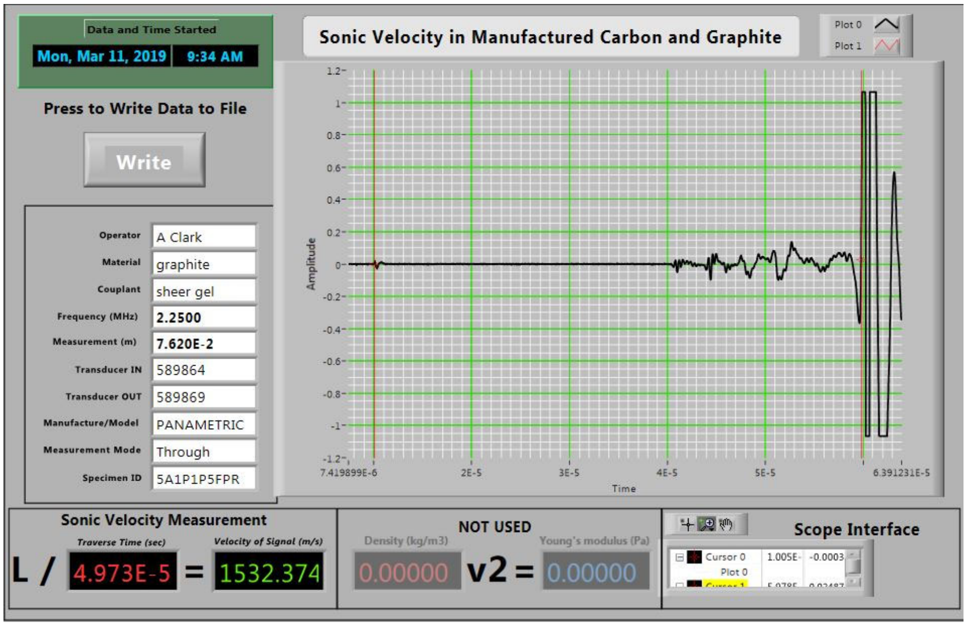


Figure 8. Typical shear wave form (Time-of-flight = 4.973E-5 s).

After establishing the sonic velocity in each graphite sample (longitudinal and shear), the elastic constants (G, E, and υ) are determined as follows.

G is written as

$$G = (v_s)^2 \cdot \rho \quad , \tag{1}$$

where G is the shear modulus, ρ is the specimen bulk density (kg/m^3), and V_s is the mean shear velocity [mean of $V_s(0°)$ and $V_s(90°)$].

E is similarly given by

$$E = \rho \cdot V_l^2 \cdot C_\mu \quad , \tag{2}$$

where E is Young's modulus, ρ is the specimen bulk density (kg/m^3), V_l is the mean longitudinal velocity, and C_μ is the Poisson ratio correction factor.

C_μ may be obtained from the following relationship:

$$C_\mu = (1+\mu)\,(1-2\mu) \,/\, (1-\mu) \quad . \tag{3}$$

ASTM C769[8] suggests a value for μ of 0.2, in which case C_μ would be 0.9.

However, in a departure from ASTM C769 and the experimental plan[6], Poisson's ratio (μ) is calculated from

$$\mu = \frac{1-\left[2\left(\frac{V_s}{V_l}\right)^2\right]}{2-\left[2\left(\frac{V_s}{V_l}\right)^2\right]} \quad , \tag{4}$$

where V_s and V_l are the mean measured shear and longitudinal velocities (m/s) respectively.

A new ASTM standard is currently being developed for determination of the elastic constants using this method.

By combining Eqs. (2), (3), and (4) we may calculate a Poisson's corrected value for E.

2.3.2 Fundamental Frequency

The elastic constants E, G, and μ were also determined using the ff method in accordance with ASTM C747[9] using a GrindoSonic Mk5. The specimens were vibrated in the flexure mode. Each specimen was measured 10 times to generate a mean ff for calculation of the Young's modulus. Figure 9 shows the experimental apparatus including the tapping hammer and piezo-electric vibration detector.

During testing the test room air temperature and humidity were 22.2°C–25°C (72°F–77°F) and 49%–54%, respectively. The dynamic Young's modulus in pascals (Pa) is given by ASTM C747[9] for a rectangular cross section beam as

$$E = A_R \cdot M \cdot f^2 / w,$$

where w is the specimen width (m), M is the specimen mass (g), f is the ff (Hz), and A_R is a function of the ratio of the dimension in the direction of vibration, t, to the length, L. Values of A_R are tabulated in ASTM C747. The flexural specimens in this work were tested in both orientations as illustrated in Figure 10. Test specimens were supported on thin, narrow parallel strips of foam mounting tape (Figure 11).

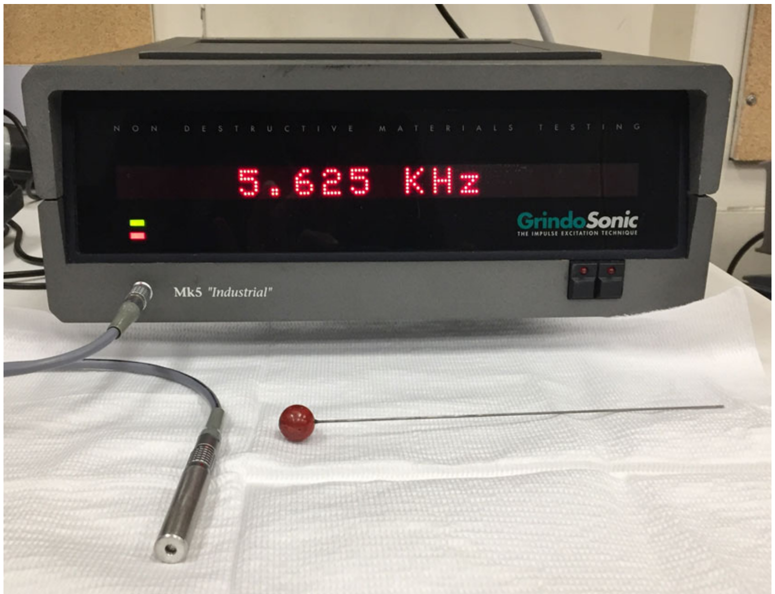


Figure 9. GrindoSonic Mk5 fundamental frequency modulus system.

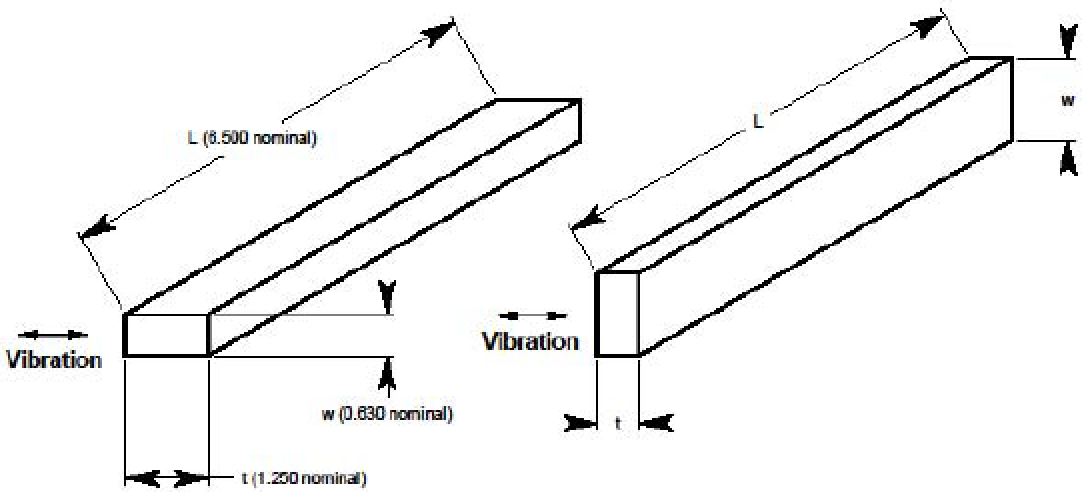


Figure 10. Specimen orientations for the flexural vibration mode defining the specimen length (L), width (W), and thickness (t). Specimen dimensions in inches

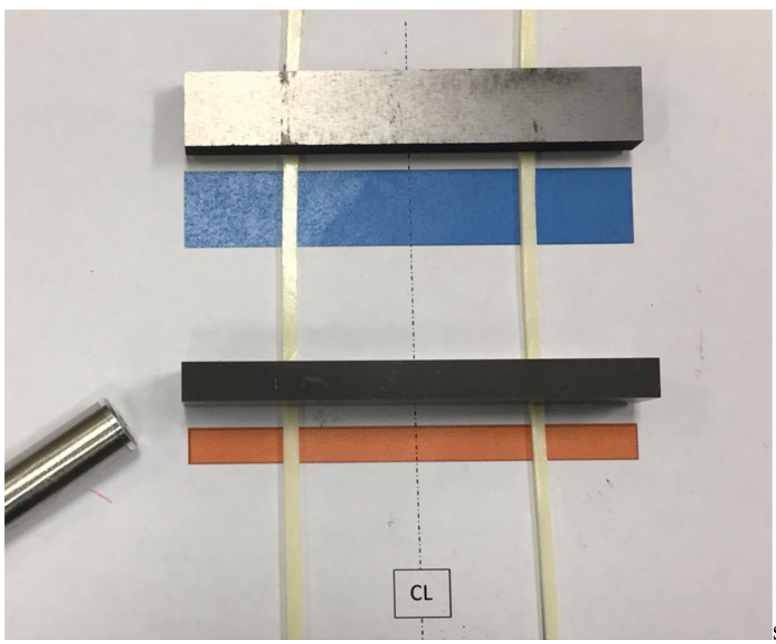


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Figure 11. Flexural specimens in two orientations simply supported by narrow strips of foam mounting tape.

The ff method was also used to determine the modulus of rigidity (shear modulus). The shear modulus in pascals is given by ASTM C747[9] as

$$G = 4.000 \cdot R \cdot f^2 \cdot L^2 \cdot \rho \ , \tag{5}$$

where ρ is the density of the specimens (kg/m3) and R is as follows:

$$R = [1 + (a^2/b^2)] \div [4 - 2.52(b/a) + 0.21(b/a)^5] \ , \tag{6}$$

where *a* is the large dimension of the specimen cross section and *b* is the small dimension of the cross section.

Determination of G requires that the specimen be vibrated in the torsion mode. To achieve this the specimen is supported on foam strips along the midpoint of its length and width (Figure 12).

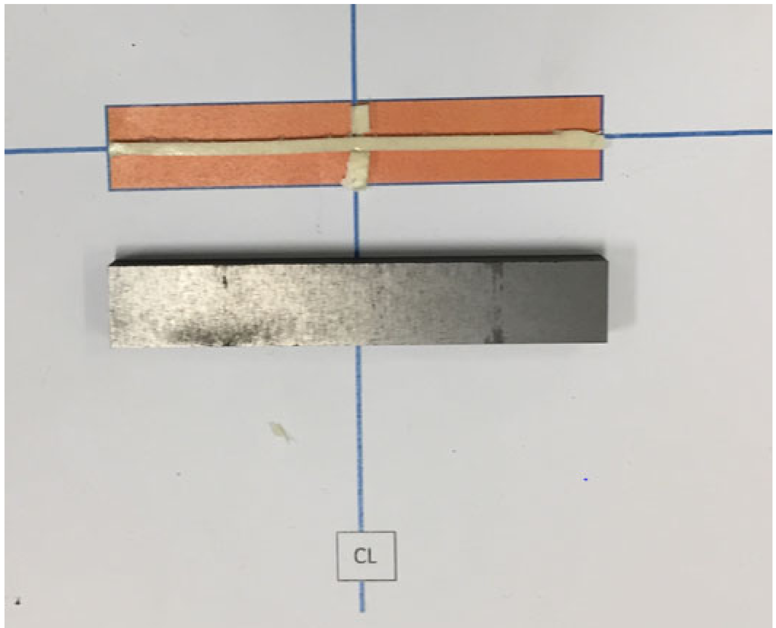

Figure 12. Specimen supported for the torsional vibration mode.

Given E and G, μ may be calculated from the following relationship (for isotropic materials only):

$$\mu = (E \div 2G) - 1 \quad . \tag{7}$$

2.4 FLEXURE STRENGTH TESTING

A drawing of the flexure specimen used is in Figure 2.[6] Flexure specimens were cut from the billet end (slab 1) and the billet center (slab 5). ASTM C651-compliant specimens were used.[10]

Flexure tests were conducted according to ASTM C651[10] at a crosshead speed of 1.25 mm/minute (0.049 in./minute) using an Instron tensile testing machine fitted with a 2 kN (449.6 lbf) load cell. The load span was set to 19.05 mm (0.75 in.), and the support span was 57.15 mm (2.25 in.). The ASTM-compliant fixture is shown in Figure 13. The ambient temperature during testing was 22.8°C (73°F), and the humidity was 55%. Before testing the specimens were dried for 2 h at 120°C–150°C (248°F–302°F).

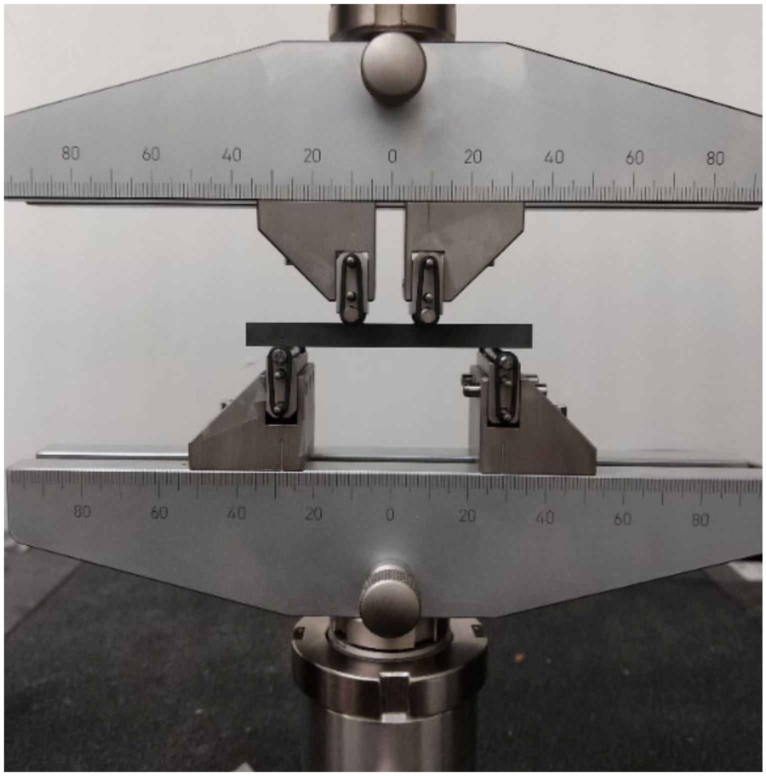

Figure 13. Typical flexure specimen under test in four-point loading.

The flexure strength is given by $\sigma_f = P \cdot L / b \cdot d^2$,

where

σ_f = flexural strength, MPa,
P = max applied load indicated by the test machine, N,
L = support span length, mm,
b = average width of specimen, mm,
d = average thickness of the specimen, mm.

3. RESULTS AND DISCUSSION

3.1 BULK DENSITY

The specimen bulk densities are given in Table A.1 (Appendix A). The bulk density subpopulations, i.e., sorted by filler orientation (WG or AG, Table A.2, Appendix A) or in-billet location (slab 1, end; or slab 5, center, Table A.3, Appendix A) were t tested to ensure they could be combined. The outcome of the t testing is given in Table 4.

In each case the subpopulations were assumed to have identical means, i.e., the null hypothesis was the mean of group 1 = the mean of group 2. Statistical t testing found no evidence to reject the null hypothesis, and thus the entire population was used to establish the mean density of 1.819 g/cm^3 (standard deviation = 0.0037). This value is very slightly larger than previously reported for the grade 2114 compressive strength population,[1] but a specimen size effect of this nature is entirely consistent with data in the literature.[11,12] A density of 1.8098 g/cm^3 for grade 2114 billet A20570 was obtained at Idaho

National Laboratory (INL), which is less than that observed here. Mersen[5] reported a density of 1.82 g/cm^3 for grade 2114, which is in good agreement with the value reported here.

Table 4. Outcome of t testing of the 2114 graphite bulk densities measured on flexure strength specimens

Population description	n	Mean kg.m^{-3}	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
AG	36	1819.47	4.24	-1.3798	2.1598	0.6616	Not significant	Not rejected
WG	36	1819.80	3.22					
PERIPHERY	48	1819.53	4.03	1.1011	2.6411	0.4146	Not significant	Not rejected
CENTER	24	1818.76	3.11					

Acronyms and abbreviations: St. Dev. = standard deviation, AG = against the grain, WG = with the grain, PERIPHERY = slab1 (end), and CENTER = slab 5.

3.2 ELASTIC CONSTANTS

3.2.1 Fundamental Frequency

3.2.1.1 Young's Modulus

The method of the ff of vibration was used with the graphite bars in two orientations per the ASTM C747.[9] The test data are given in Table A.4 (Appendix A). The two populations gave slightly different mean Young's moduli despite being calculated using appropriate geometric constants (Sect. 2.3.2.). Table 5 gives the population statistics and t testing outcome for the assumed null hypothesis of mean $\bar{\chi}_{\mathrm{Eupright}} = \bar{\chi}_{\mathrm{Eflat}}$. Based on the t testing outcome, the null hypothesis is rejected, and it is assumed that the two means are different. The ASTM standard for four-point loading[10] has the beam in a "flat" orientation for testing. Consequently, the flat geometry modulus population was selected here for further interrogation and is given in Table A.5 (Appendix A).

Table 5. Population statistics and outcome of t testing of the 2114 graphite Young's moduli (by fundamental frequency method) measured on compressive strength specimens

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
Upright	72	10.21	0.35	0.063015	0.288985	0.0025	Very significant	Rejected
Flat	72	10.03	0.33					

St. Dev. = standard deviation.

The flat geometry population was t tested; the null hypothesis was $\bar{\chi}_{\mathrm{E(flat)AG}} = \bar{\chi}_{\mathrm{E(flat)WG}}$. The outcome of the t test is in Table 6. The difference between the two means was found to be very significant and the null hypothesis was rejected. Examination of Table 6 shows that the graphite is stiffer in the WG direction than in the AG direction, although the difference is small. This difference is expected and explained by the preferred orientation of the filler particles during forming and the grain/crystal bond anisotropy (covalent bonding in-plane, van-der-Waals bonds between planes).

Table 6. Population statistics and outcome of t testing of the 2114 graphite Young's moduli (by fundamental frequency method) measured on flexural strength specimens in the flat orientation

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
Flat AG	36	9.92	0.31	-0.3781	-0.0819	0.0028	Very significant	Rejected
Flat WG	36	10.15	0.32					

Acronyms and abbreviations: St. Dev. = standard deviation, AG = against the grain, and WG = with the grain.

To investigate possible in-billet property variations the moduli (ff method) for the billet end (slab 1) was compared to the billet center (slab 5). Because we have shown that $E_{flat} \neq E_{upright}$ and E(WG) ≠ E(AG), the comparison was made using only the flat geometry WG data.

Only the experimental data for the flat orientation WG samples are reported in Table A.6 (Appendix A), and the outcome of t testing is given in Table 7.

This outcome (Table 7) suggests there is no anisotropy in the Young's moduli data. However, a similar t test of the E_{flat}AG data (Table A.7, Appendix A), testing the null hypothesis that $\bar{\chi}_{FLAT}(center)\boldsymbol{AG} = \bar{\chi}_{FLAT}(end)\boldsymbol{AG}$ showed the difference in the two means to be extremely statistically significant and the null hypothesis was rejected (Table 8).

Table 7. Population statistics and outcome of t testing of the 2114 graphite Young's moduli (by fundamental frequency method) measured on flexural strength specimens in the flat orientation sorted by grain orientation (WG) and in-billet position

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
Flat WG_{End}	24	10.09	0.37	-0.3882	0.0682	0.1633	Not statistically significant	Not rejected
Flat WG_{Center}	12	10.25	0.16					

Acronyms and abbreviations: St. Dev. = standard deviation and WG = with the grain.

Table 8. Population statistics and outcome of t testing of the 2114 graphite Young's moduli (by fundamental frequency method) measured on flexural strength specimens in the flat orientation sorted by grain orientation (AG) and in-billet position

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
Flat AG_{End}	24	9.81	0.29	-0.5317	-0.1483	0.001	Extremely statistically significant	Rejected
Flat AG_{Center}	12	10.15	0.21					

Acronyms and abbreviations: St. Dev. = standard deviation and AG = against the grain.

Similar t tests of the data from the upright orientation, i.e., the null hypotheses $\bar{\chi}_{UPRIGHT}(end)AG = \bar{\chi}_{UPRIGHT}(center)AG$ and $\bar{\chi}_{UPRIGHT}(end)WG = \bar{\chi}_{UPRIGHT}(center)WG$ found the same thing, i.e., comparing end to center data, WG data suggest isotropy, but the AG data suggest slight anisotropy. On balance, grade 2114 is not totally isotropic, but the variation is extremely small.

3.2.1.2 Shear Modulus

The ff of vibration in the torsional mode allows the calculation of the shear modulus (modulus of rigidity). The calculated values of G are in Appendix A, Table A.8 (sorted by grain orientation). To determine whether there was an effect of grain orientation (AG/WG) on shear modulus, the null hypothesis $\bar{\chi}_{\mathrm{G}_{AG}} = \bar{\chi}_{\mathrm{E}_{WG}}$ was t tested. The outcome of the t test is given in Table 9.

Table 9. Population statistics and outcome of t testing of the 2114 graphite shear moduli (by fundamental frequency method) measured on flexural strength specimens in the torsional mode

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
G_{AG}	36	4.22	0.08	-0.0453	0.0253	0.5743	Not statistically significant	Not rejected
G_{WG}	36	4.23	0.07					

Acronyms and abbreviations: St. Dev. = standard deviation, G_{AG} = shear modulus measured against the grain, and G_{WG} = shear modulus measured with the grain.

Based on the outcome of t testing the null hypothesis was not rejected, and it was assumed grain orientation had no effect on the shear modulus. This is reasonable as both orientations would be predominantly shearing along the crystallographic basal planes. Combining the populations gives a mean shear modulus of 4.228 GPa (standard deviation = 0.073 GPa).

To establish whether the shear modulus varied from end to center of the billet, the data in Table A.9 was t tested to establish any difference. The null hypothesis was taken as $\bar{\chi}_{G_{end}} = \bar{\bar{\chi}}_{G_{center}}$, and based on the test outcome (Table 10), the null hypothesis was rejected, and it was assumed the grade 2114 graphite varied slightly along the length of the billet.

The ASTM standard specification for nuclear graphite[13] gives the maximum permissible isotropy ratio (based on the coefficient of thermal expansion) for an isotropic nuclear graphite to be 1.1. Although E and G isotropy ratios are not addressed in the standard specification,[13] the variations reported here are much less than 10%.

Table 10. Population statistics and outcome of t testing of the 2114 graphite shear moduli (by fundamental frequency method) measured on flexural strength specimens in the torsional mode for effect of in-billet location

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
G_{end}	48	4.21	0.08	-0.0846	0.0154	0.0053	very statistically significant	Rejected
G_{center}	24	4.26	0.04					

Acronyms and abbreviations: St. Dev. = standard deviation, G_{end} = shear modulus at the end of the billet, and G_{center} = shear modulus at the center of the billet.

3.2.1.3 Poisson's Ratio

The material's Poisson's ratio may be calculated knowing the Young's and shear moduli [Eq. (7)]. Calculated Poisson's ratio values (for μ calculated from data for FLAT and UPRIGHT oriented beams) are given in Table A.10 of Appendix A. The population means were t tested to verify the null hypothesis $\bar{X}_{\mu UPRIGHT} = \bar{X}_{\mu_{FLAT}}$. The outcome of the t testing is in Table 11. The null hypothesis was rejected, and the difference in the means was extremely statistically significant.

Table 11. Population statistics and outcome of t testing of the 2114 graphite Poisson's ratio (by fundamental frequency method) measured on compressive strength specimens

Population description	n	Mean	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
$\mu_{Upright}$	72	0.21	0.03	0.0101	0.0299	0.0001	Extremely statistically significant	Rejected
μ_{Flat}	72	0.19	0.03					

Acronyms and abbreviations: St. Dev. = standard deviation, $\mu_{Upright}$ = Poisson's ratio measured in an upright orientation, and μ_{Flat} = Poisson's ratio measured from a flat orientation.

Such an outcome is not surprising as the reported μ value is calculated from the Young's moduli data (which also shows a similar specimen geometry dependency).

The ASTM standard for four-point loading[10] has the beam in a "flat" orientation for testing. Consequently, the "flat" geometry Poisson's ratio population was selected for further interrogation (the test data are given in Appendix A, Table A.11). The materials anisotropy was checked, the null hypothesis was $\bar{X}_{\mu(\text{flat})\text{AG}} = \bar{X}_{\mu(\text{flat})\text{WG}}$. The outcome of the t test is given in Table 12 and suggests the means are dissimilar, i.e., $\bar{X}_{\mu(\text{flat})\text{AG}} \neq \bar{X}_{\mu(\text{flat})\text{WG}}$.

Table 12. Population statistics and outcome of t testing of the 2114 graphite Poisson's ratio (by fundamental frequency method) measured on flexural strength specimens in the flat orientation, AG against WG

Population description	n	Mean	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
μ_{AG}	36	0.17	0.02	-0.0420	-0.0180	<0.0001	Extremely statistically significant	Rejected
μ_{WG}	36	0.20	0.03					

Acronyms and abbreviations: AG = against the grain, WG = with the grain, St. Dev. = standard deviation, μ_{AG} = Poisson's ratio measured against the grain, and μ_{WG} = Poisson's ratio measured with the grain.

Since $\bar{X}_{\mu(\text{flat})\text{AG}} \neq \bar{X}_{\mu(\text{flat})\text{WG}}$, only the WG Poisson's ratio subpopulation was used to assess differences due to in-billet location. The end and center subpopulations (Table A.12 in Appendix A) were t tested and the difference between the means was statistically significant (Table 13).

Table 13. Population statistics and outcome of t testing, WG only, of the 2114 graphite Poisson's ratio (by fundamental frequency method) measured on flexural strength specimens in the flat orientation for effect of position (end against center)

Population description	n	Mean	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
$\mu_{WG,END}$	24	0.20	0.03	0.0018	0.0382	00322	Statistically significant	Rejected
$\mu_{WG,CENTER}$	12	0.18	0.01					

Acronyms and abbreviations: WG = with the grain, St. Dev. = standard deviation, $\mu_{WG,END}$ = Poisson's ratio measured with the grain from an end specimen, and $\mu_{WG,CENTER}$ = Poisson's ratio measured with the grain from a center specimen.

The trend in Poisson's ratio (flat specimens, WG orientation) suggests some variation from billet center to edge (Table 13). This result is contrary to that seen in the Young's modulus data (Table 7) but in agreement with the G data (Table 10). Thus, the observed variation is expected because μ is calculated from E and G [Eq. (7)]. However, the variation in Poisson's ratio is small, and thus the graphite is still considered to be isotropic as defined in ASTM D7219.

3.2.2 Sonic Velocity

The test geometry of the flexure strength beam allows determination of the elastic constants both by the ff of vibration (ASTM C747[9]) and the sonic velocity or TOF (ASTM C769[8]). Thus, we can compare the two methods for obtaining the elastic constants and look for any equivalence.

Table A.13 (Appendix A) gives the elastic constants derived from the sonic velocity (TOF) for the grade 2114 flexure bars. These were further sorted by grain orientation, with results reported in Table A.14 and Table A.15 of Appendix A. The AG and WG population mean and standard deviation are given in Table 14. The summary data in Table 14 show in each case the elastic constant is slightly greater in the WG specimen orientation. This inequality was t tested,[4] and the outcomes of t testing are given in Table 15 (for G) on μ, Table 16 (for μ), and Table 17 (for $E_{Poisson's\ Corrected}$). In each case the null hypothesis was $\bar{X}_{AG} = \bar{X}_{WG}$.

Table 14. Sonic elastic constant's population statistics

Population statistic	Sonic Elastic Constants					
	Shear modulus $G = \rho \upsilon_s^2$ GPa		Poisson's ratio $\mu=(1-[2(\nu_s/\nu_l)2])/(2-[2(\nu_s/\nu_l)2])$		Poisson's corrected elastic modulus $E=\rho V_l^2 \cdot [(1+\mu)(1-2\mu)/(1-\mu)]$ GPa	
	AG	WG	AG	WG	AG	WG
Mean	4.25	4.27	0.19	0.20	10.13	10.26
Standard deviation	0.08	0.09	0.01	0.01	0.24	0.26
Number in population	36	36	36	36	36	36

Acronyms and abbreviations: AG = against the grain and WG = with the grain.

Table 15. Population statistics and outcome of t testing for sonic shear moduli (G) data from testing in the with and against the grain directions (WG and AG)

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
G_{AG}	36	4.25	0.08	-0.060	0.020	0.3224	Not statistically significant	Not rejected
G_{WG}	36	4.27	0.09					

St. Dev. = standard deviation.

The result for G (Table 15) agrees with the t test performed previously for the G data from ff testing (Table 9). The null hypothesis cannot be rejected, and we have evidence that grain (filler) orientation does not affect the value of shear modulus, G. A similar comparison of Poisson's ratio, μ, from the sonic velocity data (Table 16) and the ff method (Table 12) shows that for both methods the data suggest $\mu_{WG} \neq \mu_{AG}$, indicating an effect of filler particle orientation on μ.

Table 16. Population statistics and outcome of t testing for sonic Poisson's ratio (μ) data from testing in the with and against the grain directions (WG and AG)

Population description	n	Mean	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
μ_{AG}	36	0.19	0.01	0.0147	0.0053	<0.0001	Extremely statistically significant	Rejected
μ_{WG}	36	0.20	0.01					

St. Dev. = standard deviation.

The t testing outcome for the corrected Young's modulus (Table 17) suggests that the null hypothesis is incorrect and should be rejected. Thus, the data suggest $E_{AG} \neq E_{WG}$. This is expected and reflects the slight texture that develops when the graphite is formed and the strong bond anisotropy of the single crystal. The observation that $E_{AG} \neq E_{WG}$ agrees with our previous data for Young's modulus from the ff method (Table 6).

Table 17. Population statistics and outcome of t testing for sonic Young's moduli [$E_{(Poisson's\ corrected)}$] data from testing in the with and against the grain directions (WG and AG)

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
E_{AG}	36	10.13	0.24	-0.2476	-0.0124	0.0308	Statistically significant	Rejected
E_{WG}	36	10.26	0.26					

St. Dev. = standard deviation.

Variations of properties with in-billet location were extensively assessed using the ff data set. Consequently, only the sonic (TOF) Poisson's corrected Young's modulus data set was examined. Table A.16 and Table A.17 of Appendix A contain the sonic (TOF) Poisson's corrected E data for the AG and WG populations, sorted by in-billet position. Note the end-of-billet specimens have specimen numbers beginning with a numeral “1,” and center-of-billet specimens have numbers beginning with a numeral “5.” For the purpose of t testing, the null hypothesis was taken as $\bar{\chi}_{E(\mu corrected)}AG(End) = \bar{\chi}_{E(\mu corrected}AG(Center)$ and $\bar{\chi}_{E(\mu corrected)}WG(End) = \bar{\chi}_{E(\mu corrected}WG(Center)$. The outcomes of the t testing are reported in Table 18 and Table 19.

The results of t testing were mixed: for the AG population the null hypothesis was rejected, and for the WG population the null hypothesis was not rejected. On balance the variation (if any) was less than 10%, and thus the graphite should be considered isotropic as defined by ASTM D7219.

Table 18. Population statistics and outcome of t testing for sonic Young’s moduli (Poisson’s corrected) data from testing in the against the grain direction (AG) sorted by in-billet position (End or Center)

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
E_{AG}(End)	24	9.639	0.214	-0.81569	-0.52631	<0.0001	Extremely statistically significant	Rejected
E_{AG}(Center)	12	10.31	0.172					

Acronyms and abbreviations: St. Dev. = standard deviation and E_{AG} = Poisson’s corrected data for Young’s moduli measured in the against the grain direction.

Table 19. Population statistics and outcome of t testing for sonic Young’s moduli (Poisson’s corrected) data from testing in the with the grain direction (WG) sorted by in-billet position (End or Center)

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
E_{WG}(End)	24	10.21	0.294	-0.32821	0.02821	0.0963	Not statistically significant	Not Rejected
E_{WG}(Center)	12	10.36	0.097					

Acronyms and abbreviations: St. Dev. = standard deviation and E_{WG} = Poisson’s corrected data for Young’s moduli measured in the with the grain direction.

Perhaps of greater interest are comparisons between ff data and the sonic velocity data. Table 20 shows the mean, standard deviation, and population size for the elastic constants obtained from the fundamental frequency method (ASTM C747[9]) and the sonic velocity (TOF) method (ASTM C769[8]).

Table 20. Comparison of the elastic constants obtained from the fundamental frequency method (ASTM C747[9]) and the sonic velocity (TOF) method (ASTM C769[8])

Elastic Constants (Both Methods)				
Property	Fundamental Frequency ASTM C747		Sonic Velocity (time-of-flight) ASTM C769	
	Mean and Standard Deviation (sample size)		Mean and Standard Deviation (sample size)	
Grain Orientation	**AG**	**WG**	**AG**	**WG**
Shear Modulus (G), GPa	4.22 (TOR)	4.23 (TOR)	4.25	4.27
	0.08 (36)	0.07 (36)	0.08 (36)	0.09 (36)
Poisson's Ratio (μ)	0.17 (FLAT)	0.20 (FLAT)	0.19	0.20
	0.02 (36)	0.03 (36)	0.01 (36)	0.01 (36)
Young's Modulus (E), GPa	9.92 (FLAT)	10.15 (FLAT)	10.13	10.26
	0.31 (36)	0.32 (36)	0.23 (36)	0.26 (36)

Acronyms and abbreviations: TOF = time-of-flight, AG = against the grain direction, WG = with the grain direction, and TOR = torsional mode vibrations, and FLAT = flat orientation.

The two methods appear to yield similar values for the elastic constants as would be expected for an isotropic, fine-grain material such as grade 2114 graphite [note the sonic velocity (TOF) value of E is Poisson's corrected]. There is some (slight) anisotropy, the WG values exceeding the AG values for both test methods. To properly compare the two test methods a series of statistical significance tests were conducted, setting the null hypothesis to $\bar{\chi}_{AG}(G)(ff) = \bar{\chi}_{AG}(G)(TOF)$ or $\bar{\chi}_{WG}(G)(ff) = \bar{\chi}_{WG}(G)(TOF)$ (Table 21 and Table 22). Similarly, for the other elastic constants (μ and E) the populations tested always were of the same grain orientation. Note also that the ff values were for the flat specimen test geometry. The outcomes of t testing for G were mixed, as were those for μ (Table 23 and Table 24) and $E_{(\mu corrected)}$ (Table 25 and Table 26).

Shear Modulus

Table 21. Population statistics and outcome of t testing for against the grain (AG) shear modulus (G) data by sonic velocity (TOF) method and fundamental frequency (ff) method

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
G_{AG}(ff)	36	4.22	0.08	-0.0676	0.0076	0.1161	Not statistically significant	Not Rejected
G_{AG}(TOF)	36	4.25	0.08					

Acronyms and abbreviations: TOF = time-of-flight and St. Dev. = standard deviation.

Table 22. Population statistics and outcome of t testing for with the grain (WG) shear modulus (G) data by sonic velocity (TOF) method and fundamental frequency (ff) method

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
G_{WG}(ff)	36	4.23	0.070	-0.0779	-0.0021	0.0389	Statistically significant	Rejected
G_{WG}(TOF)	36	4.27	0.090					

Acronyms and abbreviations: TOF = time-of-flight and St. Dev. = standard deviation.

Poisson's Ratio

Table 23. Population statistics and outcome of t testing for against the grain (AG) Poisson's ratio (μ) data by sonic velocity (TOF) method and fundamental frequency (ff) method

Population description	n	Mean	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
μ_{AG}(ff)	36	0.17	0.02	-0.0274	-0.0126	>0.0001	Extremely statistically significant	Rejected
μ_{AG}(TOF)	36	0.19	0.01					

Acronyms and abbreviations: TOF = time-of-flight and St. Dev. = standard deviation.

Table 24. Population statistics and outcome of t testing for with the grain (WG) Poisson's ratio (μ) data by sonic velocity (TOF) method and fundamental frequency (ff) method

Population description	N	Mean	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
μ_{WG}(ff)	36	0.2	0.030	-0.0105	0.0105	1.000	Not Statistically significant	Not rejected
μ_{WG}(TOF)	36	0.2	0.010					

Acronyms and abbreviations: TOF = time-of-flight and St. Dev. = standard deviation.

Corrected Young's Modulus

Table 25. Population statistics and outcome of t testing for against the grain (AG) Young's modulus (E) data by sonic velocity (TOF) method (Poisson's ratio corrected E) and fundamental frequency (ff) method

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
E_{AG}(ff)	36	9.92	0.31	-0.3383	-0.0817	0.0017	Very statistically significant	Rejected
E_{AG}(TOF)	36	10.13	0.23					

Acronyms and abbreviations: TOF = time-of-flight and St. Dev. = standard deviation.

Table 26. Population statistics and outcome of t testing for with the grain (WG) Young's modulus (E) data by sonic velocity (TOF) method (Poisson's ratio corrected E) and fundamental frequency (ff) method

Population description	n	Mean GPa	St. Dev.	95% confidence interval on difference of means		Calculated "P" value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
E_{WG}(ff)	36	10.15	0.32	-0.247	0.0271	0.1139	Not Statistically significant	Not Rejected
E_{WG}(TOF)	36	10.26	0.26					

Acronyms and abbreviations: TOF = time-of-flight and St. Dev. = standard deviation.

Billet Data Comparison—E(ff) and G(ff)

On balance the variation (if any) between the test methods was less than 10%, as would be expected for an isotropic graphite (provided the Poisson corrected value of E is used for the comparison). Data are available for the combined AG and WG E and G modulus values for billet 20570 from testing at INL obtained by the ff method (C747). Data for billet 20570 is compared to the data reported here for billet 116310 (Table A.14 and Table A.18 of Appendix A).

Table 27 reports the mean Young's modulus and shear modulus determined for billets 116310 and 20570 for combined WG and AG specimens. For billet 116310 the Young's modulus was determined using the flat specimen orientation, and the shear modulus was determined using the torsional support. Comparing the means in Table 27 shows that good agreement was attained for the elastic moduli of the two billets.

Table 27. Data for mean Young's modulus and shear modulus for billets 116310 and 20570 (fundamental frequency method only)

Attribute or Property	Billet Number	
	116310	20570
Mean Young's Modulus, E (GPa)	10	9.9
Standard Deviation, Young's Modulus, E (GPa)	0.33	0.37
Number of Specimens	72	190
Mean Shear Modulus, G (GPa)	4.23	4.14
Standard Deviation, Shear Modulus, G (GPa)	0.5	0.07
Number of Specimens	72	190

3.3 FLEXURE STRENGH

The flexure strength test data for billet 116310 are in Table A.18 (Appendix A). To determine whether there was any anisotropy in the billet, t testing for the AG and WG orientations was conducted. Locational variations (i.e., between the billet center and end) were extensively investigated with the elastic constants data. Variations noted were <10%, and so the graphite was considered isotropic, and all flexure strength data were combined. The significance test results for the AG and WG flexure strength are given in Table 28. The t test applies to the null hypothesis $\bar{\chi}\sigma f(AG) = \bar{\chi}\sigma f(WG)$, and there is statistically significant evidence to reject the null hypothesis. However, the differences between the AG and WG means is small (<10%), and thus, the graphite is considered isotropic and all the flexural strength data have been combined.

Table 28. Population statistics and outcome of t testing for with and against the grain (WG and AG) flexure strength (σ_f) of billet 116310

Population description	n	Mean MPa	St. Dev.	95% confidence interval on difference of means		Calculated P value	Terminology (per Table 1)	Null hypothesis verdict
				Min	Max			
σ_f (AG)	36	41.95	3.13	-2.7872	-0.0126	0.048	Statistically significant	Rejected
σ_f (WG)	36	43.35	2.76					

Acronyms and abbreviations: St. Dev. = standard deviation.

The combined population of 72 flexure test bars from billet 116310 are compared to the previously tested billet (20570) in Table 29.

Table 29. Comparison of the mean four-point loading flexural strength of billets 116310 and 20570 (Mersen grade 2114)

Characteristic	Billet Number	
	116310	20570
Mean flexural strength, σ_f (MPa)	42.62	40.18
Standard deviation, flexural strength, σ_f (MPa)	3.01	2.44
Number of specimens	72	190

The difference between the flexural strength of the two test sets was found to be statistically significant but is attributed to the smaller stressed volume in the case of the ORNL testing, where the loading span was 57 mm compared to the larger 60 mm used for billet 20570. The difference is small (~ 6%), and thus the flexural strength compares well.

4. SUMMARY AND CONCLUSIONS

The following conclusions may be drawn from this work.

1. Flexural strength and elastic constants [by ff and ultrasonic velocity (TOF) testing] of 72 grade 2114 graphite specimens with AG or WG orientations from billet 116310 end or center locations have been successfully tested.

2. Data for the flexural strength, bulk density, Poisson's ratio, shear modulus and Young's modulus corrected (for υ) are reported.

3. Statistical significance testing showed the billet to be very slightly anisotropic with respect to strength and elastic properties, the noted variations were less than the 10% allowed by the ASTM standard specification,[13] and thus the graphite should be considered an isotropic grade.

4. The small anisotropy noted in the elastic properties was attributed to crystal bond anisotropy and the slight alignment of the filler during forming.

5. For this grade, the two elastic constants test methods, ff (flat beam geometry) and ultrasonic velocity (TOF)—Poisson's corrected Young's modulus, gave comparable data.

6. Agreement between these and prior data for elastic constants and flexural strength was good.

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APPENDIX A. EXPERIMENTAL DATA AND CALCULATED VALUES

APPENDIX A. EXPERIMENTAL DATA AND CALCULATED VALUES

Table A.1. Density data measured on the flexure bars

Specimen number	Grain orientation	Mean dimensions, mm			Volume	Mass	Density	
		Width	Thickness	Length	m^3	g	$g.cm^{-3}$	$kg.m^{-3}$
1A1P1P1F	Parallel (AG)	12.634	6.424	76.193	7.62E-08	11.2317	1.816	1816
1A1P1P3F	Parallel (AG)	12.640	6.425	76.195	7.62E-08	11.2310	1.815	1815
1A1P1P5F	Parallel (AG)	12.643	6.424	76.163	7.62E-08	11.2501	1.819	1819
1A1T2L2F	Transverse (WG)	12.637	6.428	76.218	7.62E-08	11.2365	1.815	1815
1A1T2L4F	Transverse (WG)	12.635	6.428	76.190	7.62E-08	11.2361	1.816	1816
1A1T2L6F	Transverse (WG)	12.642	6.423	76.210	7.62E-08	11.2434	1.817	1817
1AIT3L2F	Transverse (WG)	12.639	6.427	76.215	7.62E-08	11.2439	1.816	1816
1AIT3L4F	Transverse (WG)	12.634	6.425	76.205	7.62E-08	11.2437	1.818	1818
1AIT3L6F	Transverse (WG)	12.634	6.426	76.195	7.62E-08	11.2580	1.820	1820
1A1P4P1F	Parallel (AG)	12.635	6.426	76.158	7.62E-08	11.2502	1.819	1819
1A1P4P3F	Parallel (AG)	12.638	6.426	76.168	7.62E-08	11.2611	1.821	1821
1A1P4P5F	Parallel (AG)	12.638	6.427	76.140	7.61E-08	11.2709	1.822	1822
1A4P1P1F	Parallel (AG)	12.636	6.426	76.215	7.62E-08	11.2459	1.817	1817
1A4P1P3F	Parallel (AG)	12.638	6.428	76.215	7.62E-08	11.2514	1.817	1817
1A4P1P5F	Parallel (AG)	12.638	6.426	76.168	7.62E-08	11.2456	1.818	1818
1A4P4P1F	Parallel (AG)	12.635	6.423	76.158	7.62E-08	11.2253	1.816	1816
1A4P4P3F	Parallel (AG)	12.637	6.427	76.203	7.62E-08	11.2378	1.816	1816
1A4P4P5F	Parallel (AG)	12.636	6.427	76.168	7.62E-08	11.2472	1.818	1818
1A4T3L2F	Transverse (WG)	12.636	6.398	76.180	7.62E-08	11.1938	1.818	1818
1A4T3L4F	Transverse (WG)	12.634	6.424	76.178	7.62E-08	11.2292	1.816	1816
1A4T3L6F	Transverse (WG)	12.643	6.425	76.195	7.62E-08	11.2798	1.823	1823
1A4T2L2F	Transverse (WG)	12.633	6.425	76.150	7.62E-08	11.2431	1.819	1819
1A4T2L4F	Transverse (WG)	12.635	6.427	76.200	7.62E-08	11.2428	1.817	1817
1A4T2L6F	Transverse (WG)	12.636	6.427	76.158	7.62E-08	11.2332	1.816	1816
1B2P1PIF	Parallel (AG)	12.637	6.428	76.160	7.62E-08	11.2568	1.820	1820
1B2P1P3F	Parallel (AG)	12.636	6.426	76.183	7.62E-08	11.3019	1.827	1827
1B2P1P5F	Parallel (AG)	12.638	6.426	76.213	7.62E-08	11.2422	1.816	1816

Table A.1. Density data measured on the flexure bars (continued)

Specimen number	Grain orientation	Mean dimensions, mm			Volume	Mass	Density	
		Width	Thickness	Length	m^3	g	$g.cm^{-3}$	$kg.m^{-3}$
1B2P4P1F	Parallel (AG)	12.637	6.427	76.198	7.62E-08	11.2632	1.820	1820
1B2P4P3F	Parallel (AG)	12.632	6.425	76.200	7.62E-08	11.2423	1.818	1818
1B2P4P5F	Parallel (AG)	12.635	6.428	76.145	7.61E-08	11.2521	1.819	1819
1B2T2L2F	Transverse (WG)	12.632	6.423	76.198	7.62E-08	11.2396	1.818	1818
1B2T2L4F	Transverse (WG)	12.639	6.425	76.180	7.62E-08	11.2154	1.813	1813
1B2T2L6F	Transverse (WG)	12.641	6.425	76.183	7.62E-08	11.2576	1.819	1819
1B2T3L2F	Transverse (WG)	12.640	6.425	76.175	7.62E-08	11.2598	1.820	1820
1B2T3L4F	Transverse (WG)	12.636	6.428	76.170	7.62E-08	11.2635	1.821	1821
1B2T3L6F	Transverse (WG)	12.648	6.425	76.155	7.62E-08	11.2387	1.816	1816
1B3P1P1F	Parallel (AG)	12.639	6.422	76.173	7.62E-08	11.3052	1.829	1829
1B3P1P3F	Parallel (AG)	12.637	6.423	76.175	7.62E-08	11.3169	1.830	1830
1B3P1P5F	Parallel (AG)	12.637	6.426	76.170	7.62E-08	11.3288	1.832	1832
1B3P4P1F	Parallel (AG)	12.633	6.425	76.173	7.62E-08	11.2232	1.815	1815
1B3P4P3F	Parallel (AG)	12.637	6.426	76.170	7.62E-08	11.2495	1.819	1819
1B3P4P5F	Parallel (AG)	12.634	6.425	76.185	7.62E-08	11.2640	1.821	1821
1B3T2L2F	Transverse (WG)	12.640	6.428	76.158	7.62E-08	11.3017	1.827	1827
1B3T2L4F	Transverse (WG)	12.636	6.427	76.208	7.62E-08	11.2902	1.824	1824
1B3T2L6F	Transverse (WG)	12.636	6.422	76.193	7.62E-08	11.2545	1.820	1820
1B3T3L2F	Transverse (WG)	12.634	6.425	76.178	7.62E-08	11.2560	1.820	1820
1B3T3L4F	Transverse (WG)	12.639	6.427	76.213	7.62E-08	11.2830	1.822	1822
1B3T3L6F	Transverse (WG)	12.640	6.427	76.190	7.62E-08	11.2862	1.824	1824
5A1P1P1F	Parallel (AG)	12.647	6.431	76.185	7.62E-08	11.2551	1.817	1817
5A1P1P3F	Parallel (AG)	12.648	6.426	76.195	7.62E-08	11.2521	1.817	1817
5A1P1P5FR	Parallel (AG)	12.648	6.431	76.205	7.62E-08	11.2535	1.815	1815
5A1P4P1F	Parallel (AG)	12.647	6.435	76.203	7.62E-08	11.2621	1.816	1816
5A1P4P3F	Parallel (AG)	12.647	6.429	76.178	7.62E-08	11.2507	1.816	1816
5A1P4P5F	Parallel (AG)	12.648	6.430	76.190	7.62E-08	11.2451	1.815	1815
5A1T2L2F	Transverse (WG)	12.651	6.433	76.180	7.62E-08	11.2596	1.816	1816
5A1T2L4F	Transverse (WG)	12.650	6.430	76.190	7.62E-08	11.2477	1.815	1815
5A1T2L6F	Transverse (WG)	12.649	6.428	76.190	7.62E-08	11.2539	1.817	1817

Table A.1. Density data measured on the flexure bars (continued)

Specimen number	Grain orientation	Mean dimensions, mm			Volume	Mass	Density	
		Width	Thickness	Length	m^3	g	$g.cm^{-3}$	$kg.m^{-3}$
5A1T3L2FR	Transverse (WG)	12.648	6.431	76.195	7.62E-08	11.2561	1.816	1816
5A1T3L4F	Transverse (WG)	12.648	6.426	76.180	7.62E-08	11.2546	1.818	1818
5A1T3L6F	Transverse (WG)	12.646	6.429	76.188	7.62E-08	11.2674	1.819	1819
5B3P1P1F	Parallel (AG)	12.647	6.426	76.188	7.62E-08	11.2692	1.820	1820
5B3P1P3F	Parallel (AG)	12.651	6.431	76.210	7.62E-08	11.2849	1.820	1820
5B3P1P5F	Parallel (AG)	12.647	6.429	76.175	7.62E-08	11.2720	1.820	1820
5B3P4P1F	Parallel (AG)	12.647	6.428	76.188	7.62E-08	11.2906	1.823	1823
5B3P4P3F	Parallel (AG)	12.647	6.430	76.168	7.62E-08	11.2933	1.823	1823
5B3P4P5FR	Parallel (AG)	12.646	6.426	76.178	7.62E-08	11.2401	1.816	1816
5B3T2L2FR	Transverse (WG)	12.648	6.423	76.183	7.62E-08	11.2972	1.825	1825
5B3T2L4F	Transverse (WG)	12.641	6.427	76.200	7.62E-08	11.2685	1.820	1820
5B3T2L6F	Transverse (WG)	12.646	6.431	76.180	7.62E-08	11.2766	1.820	1820
5B3T3L2F	Transverse (WG)	12.649	6.429	76.188	7.62E-08	11.2707	1.819	1819
5B3T3L4F	Transverse (WG)	12.649	6.454	76.183	7.62E-08	11.3228	1.821	1821
5B3T3L6F	Transverse (WG)	12.648	6.433	76.210	7.62E-08	11.3159	1.825	1825

Table A.2. Mersen 2114 graphite bulk density from flexure specimens, sorted by filler orientation

Specimen number	Grain orientation	Density		Specimen number	Grain orientation	Density	
		$g.cm^{-3}$	$kg.m^{-3}$			$g.cm^{-3}$	$kg.m^{-3}$
1A1P1P1F	Parallel (AG)	1.816	1816	1A1T2L2F	Transverse (WG)	1.815	1815
1A1P1P3F	Parallel (AG)	1.815	1815	1A1T2L4F	Transverse (WG)	1.816	1816
1A1P1P5F	Parallel (AG)	1.819	1819	1A1T2L6F	Transverse (WG)	1.817	1817
1A1P4P1F	Parallel (AG)	1.819	1819	1AIT3L2F	Transverse (WG)	1.816	1816
1A1P4P3F	Parallel (AG)	1.821	1821	1AIT3L4F	Transverse (WG)	1.818	1818
1A1P4P5F	Parallel (AG)	1.822	1822	1AIT3L6F	Transverse (WG)	1.820	1820
1A4P1P1F	Parallel (AG)	1.817	1817	1A4T3L2F	Transverse (WG)	1.818	1818
1A4P1P3F	Parallel (AG)	1.817	1817	1A4T3L4F	Transverse (WG)	1.816	1816
1A4P1P5F	Parallel (AG)	1.818	1818	1A4T3L6F	Transverse (WG)	1.823	1823
1A4P4P1F	Parallel (AG)	1.816	1816	1A4T2L2F	Transverse (WG)	1.819	1819
1A4P4P3F	Parallel (AG)	1.816	1816	1A4T2L4F	Transverse (WG)	1.817	1817
1A4P4P5F	Parallel (AG)	1.818	1818	1A4T2L6F	Transverse (WG)	1.816	1816
1B2P1PIF	Parallel (AG)	1.820	1820	1B2T2L2F	Transverse (WG)	1.818	1818
1B2P1P3F	Parallel (AG)	1.827	1827	1B2T2L4F	Transverse (WG)	1.813	1813
1B2P1P5F	Parallel (AG)	1.816	1816	1B2T2L6F	Transverse (WG)	1.819	1819
1B2P4P1F	Parallel (AG)	1.820	1820	1B2T3L2F	Transverse (WG)	1.820	1820
1B2P4P3F	Parallel (AG)	1.818	1818	1B2T3L4F	Transverse (WG)	1.821	1821
1B2P4P5F	Parallel (AG)	1.819	1819	1B2T3L6F	Transverse (WG)	1.816	1816
1B3P1P1F	Parallel (AG)	1.829	1829	1B3T2L2F	Transverse (WG)	1.827	1827
1B3P1P3F	Parallel (AG)	1.830	1830	1B3T2L4F	Transverse (WG)	1.824	1824
1B3P1P5F	Parallel (AG)	1.832	1832	1B3T2L6F	Transverse (WG)	1.820	1820
1B3P4P1F	Parallel (AG)	1.815	1815	1B3T3L2F	Transverse (WG)	1.820	1820
1B3P4P3F	Parallel (AG)	1.819	1819	1B3T3L4F	Transverse (WG)	1.822	1822
1B3P4P5F	Parallel (AG)	1.821	1821	1B3T3L6F	Transverse (WG)	1.824	1824
5A1P1P1F	Parallel (AG)	1.817	1817	5A1T2L2F	Transverse (WG)	1.816	1816
5A1P1P3F	Parallel (AG)	1.817	1817	5A1T2L4F	Transverse (WG)	1.815	1815
5A1P1P5FR	Parallel (AG)	1.815	1815	5A1T2L6F	Transverse (WG)	1.817	1817
5A1P4P1F	Parallel (AG)	1.816	1816	5A1T3L2FR	Transverse (WG)	1.816	1816
5A1P4P3F	Parallel (AG)	1.816	1816	5A1T3L4F	Transverse (WG)	1.818	1818
5A1P4P5F	Parallel (AG)	1.815	1815	5A1T3L6F	Transverse (WG)	1.819	1819

Table A.2. Mersen 2114 graphite Bulk Density from flexure specimens, sorted by filler orientation (continued)

Specimen number	Grain orientation	Density		Specimen number	Grain orientation	Density	
		g.cm^{-3}	kg.m^{-3}			g.cm^{-3}	kg.m^{-3}
5B3P1P1F	Parallel (AG)	1.820	1820	5B3T2L2FR	Transverse (WG)	1.825	1825
5B3P1P3F	Parallel (AG)	1.820	1820	5B3T2L4F	Transverse (WG)	1.820	1820
5B3P1P5F	Parallel (AG)	1.820	1820	5B3T2L6F	Transverse (WG)	1.820	1820
5B3P4P1F	Parallel (AG)	1.823	1823	5B3T3L2F	Transverse (WG)	1.819	1819
5B3P4P3F	Parallel (AG)	1.823	1823	5B3T3L4F	Transverse (WG)	1.821	1821
5B3P4P5FR	Parallel (AG)	1.816	1816	5B3T3L6F	Transverse (WG)	1.825	1825

Table A.3. Mersen 2114 graphite bulk density from flexure specimens, sorted by location within the billet (end=1, center=5).

Specimen number	Grain orientation	Density		Specimen number	Grain orientation	Density	
		g.cm^{-3}	kg.m^{-3}			g.cm^{-3}	kg.m^{-3}
1A1P1P1F	Parallel (AG)	1.816	1816	5A1P1P1F	Parallel (AG)	1.817	1817
1A1P1P3F	Parallel (AG)	1.815	1815	5A1P1P3F	Parallel (AG)	1.817	1817
1A1P1P5F	Parallel (AG)	1.819	1819	5A1P1P5FR	Parallel (AG)	1.815	1815
1A1P4P1F	Parallel (AG)	1.819	1819	5A1P4P1F	Parallel (AG)	1.816	1816
1A1P4P3F	Parallel (AG)	1.821	1821	5A1P4P3F	Parallel (AG)	1.816	1816
1A1P4P5F	Parallel (AG)	1.822	1822	5A1P4P5F	Parallel (AG)	1.815	1815
1A4P1P1F	Parallel (AG)	1.817	1817	5B3P1P1F	Parallel (AG)	1.820	1820
1A4P1P3F	Parallel (AG)	1.817	1817	5B3P1P3F	Parallel (AG)	1.820	1820
1A4P1P5F	Parallel (AG)	1.818	1818	5B3P1P5F	Parallel (AG)	1.820	1820
1A4P4P1F	Parallel (AG)	1.816	1816	5B3P4P1F	Parallel (AG)	1.823	1823
1A4P4P3F	Parallel (AG)	1.816	1816	5B3P4P3F	Parallel (AG)	1.823	1823
1A4P4P5F	Parallel (AG)	1.818	1818	5B3P4P5FR	Parallel (AG)	1.816	1816
1B2P1PIF	Parallel (AG)	1.820	1820	5A1T2L2F	Transverse (WG)	1.816	1816
1B2P1P3F	Parallel (AG)	1.827	1827	5A1T2L4F	Transverse (WG)	1.815	1815
1B2P1P5F	Parallel (AG)	1.816	1816	5A1T2L6F	Transverse (WG)	1.817	1817
1B2P4P1F	Parallel (AG)	1.820	1820	5A1T3L2FR	Transverse (WG)	1.816	1816
1B2P4P3F	Parallel (AG)	1.818	1818	5A1T3L4F	Transverse (WG)	1.818	1818
1B2P4P5F	Parallel (AG)	1.819	1819	5A1T3L6F	Transverse (WG)	1.819	1819
1B3P1P1F	Parallel (AG)	1.829	1829	5B3T2L2FR	Transverse (WG)	1.825	1825
1B3P1P3F	Parallel (AG)	1.830	1830	5B3T2L4F	Transverse (WG)	1.820	1820
1B3P1P5F	Parallel (AG)	1.832	1832	5B3T2L6F	Transverse (WG)	1.820	1820
1B3P4P1F	Parallel (AG)	1.815	1815	5B3T3L2F	Transverse (WG)	1.819	1819
1B3P4P3F	Parallel (AG)	1.819	1819	5B3T3L4F	Transverse (WG)	1.821	1821
1B3P4P5F	Parallel (AG)	1.821	1821	5B3T3L6F	Transverse (WG)	1.825	1825
1A1T2L2F	Transverse (WG)	1.815	1815				
1A1T2L4F	Transverse (WG)	1.816	1816				
1A1T2L6F	Transverse (WG)	1.817	1817				
1AIT3L2F	Transverse (WG)	1.816	1816				
1AIT3L4F	Transverse (WG)	1.818	1818				

Table A.3. Mersen 2114 graphite bulk density from flexure specimens, sorted by location within the billet (end=1, center=5) (continued)

Specimen number	Grain orientation	Density		Specimen number	Grain orientation	Density	
		g.cm^{-3}	kg.m^{-3}			g.cm^{-3}	kg.m^{-3}
1AIT3L6F	Transverse (WG)	1.820	1820				
1A4T3L2F	Transverse (WG)	1.818	1818				
1A4T3L4F	Transverse (WG)	1.816	1816				
1A4T3L6F	Transverse (WG)	1.823	1823				
1A4T2L2F	Transverse (WG)	1.819	1819				
1A4T2L4F	Transverse (WG)	1.817	1817				
1A4T2L6F	Transverse (WG)	1.816	1816				
1B2T2L2F	Transverse (WG)	1.818	1818				
1B2T2L4F	Transverse (WG)	1.813	1813				
1B2T2L6F	Transverse (WG)	1.819	1819				
1B2T3L2F	Transverse (WG)	1.820	1820				
1B2T3L4F	Transverse (WG)	1.821	1821				
1B2T3L6F	Transverse (WG)	1.816	1816				
1B3T2L2F	Transverse (WG)	1.827	1827				
1B3T2L4F	Transverse (WG)	1.824	1824				
1B3T2L6F	Transverse (WG)	1.820	1820				
1B3T3L2F	Transverse (WG)	1.820	1820				
1B3T3L4F	Transverse (WG)	1.822	1822				
1B3T3L6F	Transverse (WG)	1.824	1824				

Table A.4. Young's moduli (by fundamental frequency method) measured on flexural strength specimens in the flat or upright geometries (billet 116310) for with and against grain orientations (WG and AG)

Specimen number	Grain orientation	E (upright)		E (flat)	
		Pa	GPa	Pa	GPa
1A1P1P1F	Parallel (AG)	9.63E+09	9.63	9.48E+09	9.48
1A1P1P3F	Parallel (AG)	9.75E+09	9.75	9.58E+09	9.58
1A1P1P5F	Parallel (AG)	9.85E+09	9.85	9.74E+09	9.74
1A1T2L2F	Transverse (WG)	1.04E+10	10.35	1.01E+10	10.14
1A1T2L4F	Transverse (WG)	1.02E+10	10.16	1E+10	10.01
1A1T2L6F	Transverse (WG)	1.01E+10	10.08	9.94E+09	9.94
1AIT3L2F	Transverse (WG)	1.05E+10	10.47	1.03E+10	10.28
1AIT3L4F	Transverse (WG)	1.06E+10	10.59	1.04E+10	10.41
1AIT3L6F	Transverse (WG)	1.05E+10	10.51	1.03E+10	10.28
1A1P4P1F	Parallel (AG)	9.93E+09	9.93	9.78E+09	9.78
1A1P4P3F	Parallel (AG)	1.01E+10	10.08	9.9E+09	9.90
1A1P4P5F	Parallel (AG)	1.02E+10	10.18	1E+10	10.00
1A4P1P1F	Parallel (AG)	1.04E+10	10.36	1.02E+10	10.19
1A4P1P3F	Parallel (AG)	1.03E+10	10.31	1.01E+10	10.11
1A4P1P5F	Parallel (AG)	1.03E+10	10.31	1.01E+10	10.10
1A4P4P1F	Parallel (AG)	1.03E+10	10.30	1.01E+10	10.14
1A4P4P3F	Parallel (AG)	1.04E+10	10.38	1.02E+10	10.19
1A4P4P5F	Parallel (AG)	1.04E+10	10.37	1.02E+10	10.18
1A4T3L2F	Transverse (WG)	9.59E+09	9.59	9.57E+09	9.57
1A4T3L4F	Transverse (WG)	9.65E+09	9.65	9.5E+09	9.50
1A4T3L6F	Transverse (WG)	1E+10	10.04	9.9E+09	9.90
1A4T2L2F	Transverse (WG)	9.67E+09	9.67	9.52E+09	9.52
1A4T2L4F	Transverse (WG)	9.57E+09	9.57	9.43E+09	9.43
1A4T2L6F	Transverse (WG)	9.53E+09	9.53	9.37E+09	9.37
1B2P1PIF	Parallel (AG)	9.77E+09	9.77	9.61E+09	9.61
1B2P1P3F	Parallel (AG)	1E+10	10.04	9.85E+09	9.85
1B2P1P5F	Parallel (AG)	9.48E+09	9.48	9.36E+09	9.36
1B2P4P1F	Parallel (AG)	9.68E+09	9.68	9.52E+09	9.52
1B2P4P3F	Parallel (AG)	9.61E+09	9.61	9.45E+09	9.45
1B2P4P5F	Parallel (AG)	9.72E+09	9.72	9.55E+09	9.55
1B2T2L2F	Transverse (WG)	1.04E+10	10.37	1.02E+10	10.17
1B2T2L4F	Transverse (WG)	1.03E+10	10.30	1.01E+10	10.11
1B2T2L6F	Transverse (WG)	1.04E+10	10.40	1.02E+10	10.22
1B2T3L2F	Transverse (WG)	1.05E+10	10.53	1.03E+10	10.33
1B2T3L4F	Transverse (WG)	1.04E+10	10.37	1.01E+10	10.15
1B2T3L6F	Transverse (WG)	1.02E+10	10.22	1E+10	10.04

Table A.4. Young's moduli (by fundamental frequency method) measured on flexural strength specimens in the flat or upright geometries (billet 116310) for with and against grain orientations (WG and AG) (continued)

Specimen number	Grain orientation	E (upright)		E (flat)	
		Pa	GPa	Pa	GPa
1B3P1P1F	Parallel (AG)	9.97E+09	9.97	9.85E+09	9.85
1B3P1P3F	Parallel (AG)	1.01E+10	10.11	9.98E+09	9.98
1B3P1P5F	Parallel (AG)	1.03E+10	10.32	1.02E+10	10.17
1B3P4P1F	Parallel (AG)	9.5E+09	9.50	9.34E+09	9.34
1B3P4P3F	Parallel (AG)	9.68E+09	9.68	9.53E+09	9.53
1B3P4P5F	Parallel (AG)	9.9E+09	9.90	9.73E+09	9.73
1B3T2L2F	Transverse (WG)	1.09E+10	10.92	1.07E+10	10.68
1B3T2L4F	Transverse (WG)	1.07E+10	10.69	1.05E+10	10.47
1B3T2L6F	Transverse (WG)	1.04E+10	10.43	1.02E+10	10.25
1B3T3L2F	Transverse (WG)	1.05E+10	10.46	1.03E+10	10.26
1B3T3L4F	Transverse (WG)	1.07E+10	10.69	1.05E+10	10.48
1B3T3L6F	Transverse (WG)	1.08E+10	10.77	1.05E+10	10.54
5A1P1P1F	Parallel (AG)	1.01E+10	10.15	9.98E+09	9.98
5A1P1P3F	Parallel (AG)	1.02E+10	10.21	1E+10	10.03
5A1P1P5FR	Parallel (AG)	1.03E+10	10.27	1.01E+10	10.09
5A1P4P1F	Parallel (AG)	1.01E+10	10.09	9.88E+09	9.88
5A1P4P3F	Parallel (AG)	1.01E+10	10.09	9.92E+09	9.92
5A1P4P5F	Parallel (AG)	1E+10	10.04	9.87E+09	9.87
5A1T2L2F	Transverse (WG)	1.06E+10	10.61	1.04E+10	10.41
5A1T2L4F	Transverse (WG)	1.06E+10	10.60	1.04E+10	10.44
5A1T2L6F	Transverse (WG)	1.05E+10	10.51	1.03E+10	10.34
5A1T3L2FR	Transverse (WG)	1.05E+10	10.52	1.03E+10	10.32
5A1T3L4F	Transverse (WG)	1.05E+10	10.53	1.03E+10	10.35
5A1T3L6F	Transverse (WG)	1.07E+10	10.69	1.05E+10	10.47
5B3P1P1F	Parallel (AG)	1.05E+10	10.48	1.03E+10	10.29
5B3P1P3F	Parallel (AG)	1.05E+10	10.49	1.03E+10	10.32
5B3P1P5F	Parallel (AG)	1.05E+10	10.47	1.03E+10	10.29
5B3P4P1F	Parallel (AG)	1.06E+10	10.62	1.04E+10	10.40
5B3P4P3F	Parallel (AG)	1.06E+10	10.61	1.04E+10	10.41
5B3P4P5FR	Parallel (AG)	1.05E+10	10.46	1.03E+10	10.31
5B3T2L2FR	Transverse (WG)	1.04E+10	10.37	1.02E+10	10.18
5B3T2L4F	Transverse (WG)	1.03E+10	10.27	1.01E+10	10.08
5B3T2L6F	Transverse (WG)	1.03E+10	10.32	1.01E+10	10.14
5B3T3L2F	Transverse (WG)	1.02E+10	10.23	1.01E+10	10.06
5B3T3L4F	Transverse (WG)	1.04E+10	10.37	1.01E+10	10.10
5B3T3L6F	Transverse (WG)	1.03E+10	10.25	1.01E+10	10.06

Table A.5. Young's moduli (by fundamental frequency method) measured on flexural strength specimens in the flat orientation (billet '116310) sorted by grain orientation

Specimen number	Grain	E (flat)		Specimen number	Grain	E (flat)	
	orientation	Pa	GPa		orientation	Pa	GPa
1A1P1P1F	Parallel (AG)	9.48E+09	9.48	1A1T2L2F	Transverse (WG)	1.01E+10	10.14
1A1P1P3F	Parallel (AG)	9.58E+09	9.58	1A1T2L4F	Transverse (WG)	1E+10	10.01
1A1P1P5F	Parallel (AG)	9.74E+09	9.74	1A1T2L6F	Transverse (WG)	9.94E+09	9.94
1A1P4P1F	Parallel (AG)	9.78E+09	9.78	1AIT3L2F	Transverse (WG)	1.03E+10	10.28
1A1P4P3F	Parallel (AG)	9.9E+09	9.90	1AIT3L4F	Transverse (WG)	1.04E+10	10.41
1A1P4P5F	Parallel (AG)	1E+10	10.00	1AIT3L6F	Transverse (WG)	1.03E+10	10.28
1A4P1P1F	Parallel (AG)	1.02E+10	10.19	1A4T3L2F	Transverse (WG)	9.57E+09	9.57
1A4P1P3F	Parallel (AG)	1.01E+10	10.11	1A4T3L4F	Transverse (WG)	9.5E+09	9.50
1A4P1P5F	Parallel (AG)	1.01E+10	10.10	1A4T3L6F	Transverse (WG)	9.9E+09	9.90
1A4P4P1F	Parallel (AG)	1.01E+10	10.14	1A4T2L2F	Transverse (WG)	9.52E+09	9.52
1A4P4P3F	Parallel (AG)	1.02E+10	10.19	1A4T2L4F	Transverse (WG)	9.43E+09	9.43
1A4P4P5F	Parallel (AG)	1.02E+10	10.18	1A4T2L6F	Transverse (WG)	9.37E+09	9.37
1B2P1PIF	Parallel (AG)	9.61E+09	9.61	1B2T2L2F	Transverse (WG)	1.02E+10	10.17
1B2P1P3F	Parallel (AG)	9.85E+09	9.85	1B2T2L4F	Transverse (WG)	1.01E+10	10.11
1B2P1P5F	Parallel (AG)	9.36E+09	9.36	1B2T2L6F	Transverse (WG)	1.02E+10	10.22
1B2P4P1F	Parallel (AG)	9.52E+09	9.52	1B2T3L2F	Transverse (WG)	1.03E+10	10.33
1B2P4P3F	Parallel (AG)	9.45E+09	9.45	1B2T3L4F	Transverse (WG)	1.01E+10	10.15
1B2P4P5F	Parallel (AG)	9.55E+09	9.55	1B2T3L6F	Transverse (WG)	1E+10	10.04
1B3P1P1F	Parallel (AG)	9.85E+09	9.85	1B3T2L2F	Transverse (WG)	1.07E+10	10.68
1B3P1P3F	Parallel (AG)	9.98E+09	9.98	1B3T2L4F	Transverse (WG)	1.05E+10	10.47
1B3P1P5F	Parallel (AG)	1.02E+10	10.17	1B3T2L6F	Transverse (WG)	1.02E+10	10.25
1B3P4P1F	Parallel (AG)	9.34E+09	9.34	1B3T3L2F	Transverse (WG)	1.03E+10	10.26
1B3P4P3F	Parallel (AG)	9.53E+09	9.53	1B3T3L4F	Transverse (WG)	1.05E+10	10.48
1B3P4P5F	Parallel (AG)	9.73E+09	9.73	1B3T3L6F	Transverse (WG)	1.05E+10	10.54
5A1P1P1F	Parallel (AG)	9.98E+09	9.98	5A1T2L2F	Transverse (WG)	1.04E+10	10.41
5A1P1P3F	Parallel (AG)	1E+10	10.03	5A1T2L4F	Transverse (WG)	1.04E+10	10.44
5A1P1P5FR	Parallel (AG)	1.01E+10	10.09	5A1T2L6F	Transverse (WG)	1.03E+10	10.34
5A1P4P1F	Parallel (AG)	9.88E+09	9.88	5A1T3L2FR	Transverse (WG)	1.03E+10	10.32
5A1P4P3F	Parallel (AG)	9.92E+09	9.92	5A1T3L4F	Transverse (WG)	1.03E+10	10.35
5A1P4P5F	Parallel (AG)	9.87E+09	9.87	5A1T3L6F	Transverse (WG)	1.05E+10	10.47

Table A.5. Young's moduli (by fundamental frequency method) measured on flexural strength specimens in the flat orientation (billet 116310) sorted by grain orientation (continued)

Specimen number	Grain	E (flat)		Specimen number	Grain	E (flat)	
	orientation	Pa	GPa		orientation	Pa	GPa
5B3P1P1F	Parallel (AG)	1.03E+10	10.29	5B3T2L2FR	Transverse (WG)	1.02E+10	10.18
5B3P1P3F	Parallel (AG)	1.03E+10	10.32	5B3T2L4F	Transverse (WG)	1.01E+10	10.08
5B3P1P5F	Parallel (AG)	1.03E+10	10.29	5B3T2L6F	Transverse (WG)	1.01E+10	10.14
5B3P4P1F	Parallel (AG)	1.04E+10	10.40	5B3T3L2F	Transverse (WG)	1.01E+10	10.06
5B3P4P3F	Parallel (AG)	1.04E+10	10.41	5B3T3L4F	Transverse (WG)	1.01E+10	10.10
5B3P4P5FR	Parallel (AG)	1.03E+10	10.31	5B3T3L6F	Transverse (WG)	1.01E+10	10.06

Table A.6. Young's moduli (by fundamental frequency method) measured on WG flexural strength specimens in the flat orientation (billet 116310) sorted by in-billet position (end vs. center)

Specimen number	Grain	E (flat)		Specimen number	Grain	E (flat)	
	orientation	Pa	GPa		orientation	Pa	GPa
1A1T2L2F	Transverse (WG)	1.01E+10	10.14	5A1T2L2F	Transverse (WG)	1.04E+10	10.41
1A1T2L4F	Transverse (WG)	1E+10	10.01	5A1T2L4F	Transverse (WG)	1.04E+10	10.44
1A1T2L6F	Transverse (WG)	9.94E+09	9.94	5A1T2L6F	Transverse (WG)	1.03E+10	10.34
1AIT3L2F	Transverse (WG)	1.03E+10	10.28	5A1T3L2FR	Transverse (WG)	1.03E+10	10.32
1AIT3L4F	Transverse (WG)	1.04E+10	10.41	5A1T3L4F	Transverse (WG)	1.03E+10	10.35
1AIT3L6F	Transverse (WG)	1.03E+10	10.28	5A1T3L6F	Transverse (WG)	1.05E+10	10.47
1A4T3L2F	Transverse (WG)	9.57E+09	9.57	5B3T2L2FR	Transverse (WG)	1.02E+10	10.18
1A4T3L4F	Transverse (WG)	9.5E+09	9.50	5B3T2L4F	Transverse (WG)	1.01E+10	10.08
1A4T3L6F	Transverse (WG)	9.9E+09	9.90	5B3T2L6F	Transverse (WG)	1.01E+10	10.14
1A4T2L2F	Transverse (WG)	9.52E+09	9.52	5B3T3L2F	Transverse (WG)	1.01E+10	10.06
1A4T2L4F	Transverse (WG)	9.43E+09	9.43	5B3T3L4F	Transverse (WG)	1.01E+10	10.10
1A4T2L6F	Transverse (WG)	9.37E+09	9.37	5B3T3L6F	Transverse (WG)	1.01E+10	10.06
1B2T2L2F	Transverse (WG)	1.02E+10	10.17				
1B2T2L4F	Transverse (WG)	1.01E+10	10.11				
1B2T2L6F	Transverse (WG)	1.02E+10	10.22				
1B2T3L2F	Transverse (WG)	1.03E+10	10.33				
1B2T3L4F	Transverse (WG)	1.01E+10	10.15				
1B2T3L6F	Transverse (WG)	1E+10	10.04				
1B3T2L2F	Transverse (WG)	1.07E+10	10.68				
1B3T2L4F	Transverse (WG)	1.05E+10	10.47				
1B3T2L6F	Transverse (WG)	1.02E+10	10.25				
1B3T3L2F	Transverse (WG)	1.03E+10	10.26				
1B3T3L4F	Transverse (WG)	1.05E+10	10.48				
1B3T3L6F	Transverse (WG)	1.05E+10	10.54				

Table A.7. Young's moduli (by fundamental frequency method) measured on AG flexural strength specimens in the flat orientation (billet 116310) sorted by in-billet position (end vs. center)

Specimen number	Grain orientation	E (flat) Pa	E (flat) GPa	Specimen number	Grain orientation	E (flat) Pa	E (flat) GPa
1A1P1P1F	Parallel (AG)	9.48E+09	9.48	5A1P1P1F	Parallel (AG)	9.98E+09	9.98
1A1P1P3F	Parallel (AG)	9.58E+09	9.58	5A1P1P3F	Parallel (AG)	1E+10	10.03
1A1P1P5F	Parallel (AG)	9.74E+09	9.74	5A1P1P5FR	Parallel (AG)	1.01E+10	10.09
1A1P4P1F	Parallel (AG)	9.78E+09	9.78	5A1P4P1F	Parallel (AG)	9.88E+09	9.88
1A1P4P3F	Parallel (AG)	9.9E+09	9.90	5A1P4P3F	Parallel (AG)	9.92E+09	9.92
1A1P4P5F	Parallel (AG)	1E+10	10.00	5A1P4P5F	Parallel (AG)	9.87E+09	9.87
1A4P1P1F	Parallel (AG)	1.02E+10	10.19	5B3P1P1F	Parallel (AG)	1.03E+10	10.29
1A4P1P3F	Parallel (AG)	1.01E+10	10.11	5B3P1P3F	Parallel (AG)	1.03E+10	10.32
1A4P1P5F	Parallel (AG)	1.01E+10	10.10	5B3P1P5F	Parallel (AG)	1.03E+10	10.29
1A4P4P1F	Parallel (AG)	1.01E+10	10.14	5B3P4P1F	Parallel (AG)	1.04E+10	10.40
1A4P4P3F	Parallel (AG)	1.02E+10	10.19	5B3P4P3F	Parallel (AG)	1.04E+10	10.41
1A4P4P5F	Parallel (AG)	1.02E+10	10.18	5B3P4P5FR	Parallel (AG)	1.03E+10	10.31
1B2P1PIF	Parallel (AG)	9.61E+09	9.61				
1B2P1P3F	Parallel (AG)	9.85E+09	9.85				
1B2P1P5F	Parallel (AG)	9.36E+09	9.36				
1B2P4P1F	Parallel (AG)	9.52E+09	9.52				
1B2P4P3F	Parallel (AG)	9.45E+09	9.45				
1B2P4P5F	Parallel (AG)	9.55E+09	9.55				
1B3P1P1F	Parallel (AG)	9.85E+09	9.85				
1B3P1P3F	Parallel (AG)	9.98E+09	9.98				
1B3P1P5F	Parallel (AG)	1.02E+10	10.17				
1B3P4P1F	Parallel (AG)	9.34E+09	9.34				
1B3P4P3F	Parallel (AG)	9.53E+09	9.53				
1B3P4P5F	Parallel (AG)	9.73E+09	9.73				

Table A.8. Shear moduli (by fundamental frequency method) measured on flexural strength specimens in the torsional vibration mode (billet 116310) sorted by grain orientation

Specimen number	Grain orientation	Shear modulus, G Pa	GPa	Specimen number	Grain orientation	Shear modulus, G Pa	GPa
1A1P1P1F	Parallel (AG)	4.12E+09	4.12	1A1T2L2F	Transverse (WG)	4.17E+09	4.17
1A1P1P3F	Parallel (AG)	4.1E+09	4.10	1A1T2L4F	Transverse (WG)	4.19E+09	4.19
1A1P1P5F	Parallel (AG)	4.19E+09	4.19	1A1T2L6F	Transverse (WG)	4.22E+09	4.22
1A1P4P1F	Parallel (AG)	4.28E+09	4.28	1AIT3L2F	Transverse (WG)	4.25E+09	4.25
1A1P4P3F	Parallel (AG)	4.3E+09	4.30	1AIT3L4F	Transverse (WG)	4.31E+09	4.31
1A1P4P5F	Parallel (AG)	4.27E+09	4.27	1AIT3L6F	Transverse (WG)	4.28E+09	4.28
1A4P1P1F	Parallel (AG)	4.26E+09	4.26	1A4T3L2F	Transverse (WG)	4.15E+09	4.15
1A4P1P3F	Parallel (AG)	4.21E+09	4.21	1A4T3L4F	Transverse (WG)	4.11E+09	4.11
1A4P1P5F	Parallel (AG)	4.13E+09	4.13	1A4T3L6F	Transverse (WG)	4.28E+09	4.28
1A4P4P1F	Parallel (AG)	4.29E+09	4.29	1A4T2L2F	Transverse (WG)	4.14E+09	4.14
1A4P4P3F	Parallel (AG)	4.23E+09	4.23	1A4T2L4F	Transverse (WG)	4.15E+09	4.15
1A4P4P5F	Parallel (AG)	4.28E+09	4.28	1A4T2L6F	Transverse (WG)	4.15E+09	4.15
1B2P1PIF	Parallel (AG)	4.16E+09	4.16	1B2T2L2F	Transverse (WG)	4.17E+09	4.17
1B2P1P3F	Parallel (AG)	4.27E+09	4.27	1B2T2L4F	Transverse (WG)	4.11E+09	4.11
1B2P1P5F	Parallel (AG)	4.09E+09	4.09	1B2T2L6F	Transverse (WG)	4.3E+09	4.30
1B2P4P1F	Parallel (AG)	4.11E+09	4.11	1B2T3L2F	Transverse (WG)	4.29E+09	4.29
1B2P4P3F	Parallel (AG)	4.12E+09	4.12	1B2T3L4F	Transverse (WG)	4.21E+09	4.21
1B2P4P5F	Parallel (AG)	4.12E+09	4.12	1B2T3L6F	Transverse (WG)	4.11E+09	4.11
1B3P1P1F	Parallel (AG)	4.3E+09	4.30	1B3T2L2F	Transverse (WG)	4.34E+09	4.34
1B3P1P3F	Parallel (AG)	4.37E+09	4.37	1B3T2L4F	Transverse (WG)	4.15E+09	4.15
1B3P1P5F	Parallel (AG)	4.36E+09	4.36	1B3T2L6F	Transverse (WG)	4.28E+09	4.28
1B3P4P1F	Parallel (AG)	4.07E+09	4.07	1B3T3L2F	Transverse (WG)	4.22E+09	4.22
1B3P4P3F	Parallel (AG)	4.15E+09	4.15	1B3T3L4F	Transverse (WG)	4.27E+09	4.27
1B3P4P5F	Parallel (AG)	4.2E+09	4.20	1B3T3L6F	Transverse (WG)	4.28E+09	4.28
5A1P1P1F	Parallel (AG)	4.21E+09	4.21	5A1T2L2F	Transverse (WG)	4.3E+09	4.30
5A1P1P3F	Parallel (AG)	4.23E+09	4.23	5A1T2L4F	Transverse (WG)	4.29E+09	4.29
5A1P1P5FR	Parallel (AG)	4.24E+09	4.24	5A1T2L6F	Transverse (WG)	4.28E+09	4.28
5A1P4P1F	Parallel (AG)	4.21E+09	4.21	5A1T3L2FR	Transverse (WG)	4.27E+09	4.27
5A1P4P3F	Parallel (AG)	4.2E+09	4.20	5A1T3L4F	Transverse (WG)	4.25E+09	4.25
5A1P4P5F	Parallel (AG)	4.2E+09	4.20	5A1T3L6F	Transverse (WG)	4.31E+09	4.31
5B3P1P1F	Parallel (AG)	4.24E+09	4.24	5B3T2L2FR	Transverse (WG)	4.28E+09	4.28
5B3P1P3F	Parallel (AG)	4.31E+09	4.31	5B3T2L4F	Transverse (WG)	4.25E+09	4.25
5B3P1P5F	Parallel (AG)	4.29E+09	4.29	5B3T2L6F	Transverse (WG)	4.26E+09	4.26
5B3P4P1F	Parallel (AG)	4.3E+09	4.30	5B3T3L2F	Transverse (WG)	4.25E+09	4.25
5B3P4P3F	Parallel (AG)	4.34E+09	4.34	5B3T3L4F	Transverse (WG)	4.24E+09	4.24
5B3P4P5FR	Parallel (AG)	4.29E+09	4.29	5B3T3L6F	Transverse (WG)	4.24E+09	4.24

Table A.9. Shear moduli (by fundamental frequency method) measured on flexural strength specimens in the torsional vibration mode (billet 116310) sorted by in-billet position

Specimen number	Grain orientation	Shear modulus, G Pa	GPa	Specimen number	Grain orientation	Shear modulus, G Pa	GPa
1A1P1P1F	Parallel (AG)	4.12E+09	4.12	5A1T2L2F	Transverse (WG)	4.3E+09	4.30
1A1P1P3F	Parallel (AG)	4.1E+09	4.10	5A1T2L4F	Transverse (WG)	4.29E+09	4.29
1A1P1P5F	Parallel (AG)	4.19E+09	4.19	5A1T2L6F	Transverse (WG)	4.28E+09	4.28
1A1P4P1F	Parallel (AG)	4.28E+09	4.28	5A1T3L2FR	Transverse (WG)	4.27E+09	4.27
1A1P4P3F	Parallel (AG)	4.3E+09	4.30	5A1T3L4F	Transverse (WG)	4.25E+09	4.25
1A1P4P5F	Parallel (AG)	4.27E+09	4.27	5A1T3L6F	Transverse (WG)	4.31E+09	4.31
1A4P1P1F	Parallel (AG)	4.26E+09	4.26	5B3T2L2FR	Transverse (WG)	4.28E+09	4.28
1A4P1P3F	Parallel (AG)	4.21E+09	4.21	5B3T2L4F	Transverse (WG)	4.25E+09	4.25
1A4P1P5F	Parallel (AG)	4.13E+09	4.13	5B3T2L6F	Transverse (WG)	4.26E+09	4.26
1A4P4P1F	Parallel (AG)	4.29E+09	4.29	5B3T3L2F	Transverse (WG)	4.25E+09	4.25
1A4P4P3F	Parallel (AG)	4.23E+09	4.23	5B3T3L4F	Transverse (WG)	4.24E+09	4.24
1A4P4P5F	Parallel (AG)	4.28E+09	4.28	5B3T3L6F	Transverse (WG)	4.24E+09	4.24
1B2P1PIF	Parallel (AG)	4.16E+09	4.16	5A1P1P1F	Parallel (AG)	4.21E+09	4.21
1B2P1P3F	Parallel (AG)	4.27E+09	4.27	5A1P1P3F	Parallel (AG)	4.23E+09	4.23
1B2P1P5F	Parallel (AG)	4.09E+09	4.09	5A1P1P5FR	Parallel (AG)	4.24E+09	4.24
1B2P4P1F	Parallel (AG)	4.11E+09	4.11	5A1P4P1F	Parallel (AG)	4.21E+09	4.21
1B2P4P3F	Parallel (AG)	4.12E+09	4.12	5A1P4P3F	Parallel (AG)	4.2E+09	4.20
1B2P4P5F	Parallel (AG)	4.12E+09	4.12	5A1P4P5F	Parallel (AG)	4.2E+09	4.20
1B3P1P1F	Parallel (AG)	4.3E+09	4.30	5B3P1P1F	Parallel (AG)	4.24E+09	4.24
1B3P1P3F	Parallel (AG)	4.37E+09	4.37	5B3P1P3F	Parallel (AG)	4.31E+09	4.31
1B3P1P5F	Parallel (AG)	4.36E+09	4.36	5B3P1P5F	Parallel (AG)	4.29E+09	4.29
1B3P4P1F	Parallel (AG)	4.07E+09	4.07	5B3P4P1F	Parallel (AG)	4.3E+09	4.30
1B3P4P3F	Parallel (AG)	4.15E+09	4.15	5B3P4P3F	Parallel (AG)	4.34E+09	4.34
1B3P4P5F	Parallel (AG)	4.2E+09	4.20	5B3P4P5FR	Parallel (AG)	4.29E+09	4.29
1B2T2L2F	Transverse (WG)	4.17E+09	4.17				
1B2T2L4F	Transverse (WG)	4.11E+09	4.11				
1B2T2L6F	Transverse (WG)	4.3E+09	4.30				
1B2T3L2F	Transverse (WG)	4.29E+09	4.29				
1B2T3L4F	Transverse (WG)	4.21E+09	4.21				
1B2T3L6F	Transverse (WG)	4.11E+09	4.11				

Table A.9. Shear moduli (by fundamental frequency method) measured on flexural strength specimens in the torsional vibration mode (billet 116310) sorted by in-billet position (continued)

Specimen number	Grain	Shear modulus, G		Specimen number	Grain	Shear modulus, G	
	orientation	Pa	GPa		orientation	Pa	GPa
1B3T2L2F	Transverse (WG)	4.34E+09	4.34				
1B3T2L4F	Transverse (WG)	4.15E+09	4.15				
1B3T2L6F	Transverse (WG)	4.28E+09	4.28				
1B3T3L2F	Transverse (WG)	4.22E+09	4.22				
1B3T3L4F	Transverse (WG)	4.27E+09	4.27				
1B3T3L6F	Transverse (WG)	4.28E+09	4.28				
1A1T2L2F	Transverse (WG)	4.17E+09	4.17				
1A1T2L4F	Transverse (WG)	4.19E+09	4.19				
1A1T2L6F	Transverse (WG)	4.22E+09	4.22				
1AIT3L2F	Transverse (WG)	4.25E+09	4.25				
1AIT3L4F	Transverse (WG)	4.31E+09	4.31				
1AIT3L6F	Transverse (WG)	4.28E+09	4.28				
1A4T3L2F	Transverse (WG)	4.15E+09	4.15				
1A4T3L4F	Transverse (WG)	4.11E+09	4.11				
1A4T3L6F	Transverse (WG)	4.28E+09	4.28				
1A4T2L2F	Transverse (WG)	4.14E+09	4.14				
1A4T2L4F	Transverse (WG)	4.15E+09	4.15				
1A4T2L6F	Transverse (WG)	4.15E+09	4.15				

Table A.10. 2114 graphite Poisson's ratio (by fundamental frequency method) measured on compressive strength specimen in the "Upright" and "Flat" test orientations

Specimen number	Grain orientation	Upright-Young's modulus E	Shear modulus, g	(Upright) Poisson's ratio, µ	Flat-Young's modulus, E	Shear modulus, g	(Flat) Poisson's ratio, µ
		GPa	GPa		GPa	GPa	
1A1P1P1F	Parallel (AG)	9.63	4.12	0.17	9.48	4.12	0.15
1A1P1P3F	Parallel (AG)	9.75	4.10	0.19	9.58	4.10	0.17
1A1P1P5F	Parallel (AG)	9.85	4.19	0.18	9.74	4.19	0.16
1A1T2L2F	Transverse (WG)	10.35	4.17	0.24	10.14	4.17	0.22
1A1T2L4F	Transverse (WG)	10.16	4.19	0.21	10.01	4.19	0.19
1A1T2L6F	Transverse (WG)	10.08	4.22	0.19	9.94	4.22	0.18
1AIT3L2F	Transverse (WG)	10.47	4.25	0.23	10.28	4.25	0.21
1AIT3L4F	Transverse (WG)	10.59	4.31	0.23	10.41	4.31	0.21
1AIT3L6F	Transverse (WG)	10.51	4.28	0.23	10.28	4.28	0.20
1A1P4P1F	Parallel (AG)	9.93	4.28	0.16	9.78	4.28	0.14
1A1P4P3F	Parallel (AG)	10.08	4.30	0.17	9.90	4.30	0.15
1A1P4P5F	Parallel (AG)	10.18	4.27	0.19	10.00	4.27	0.17
1A4P1P1F	Parallel (AG)	10.36	4.26	0.22	10.19	4.26	0.20
1A4P1P3F	Parallel (AG)	10.31	4.21	0.22	10.11	4.21	0.20
1A4P1P5F	Parallel (AG)	10.31	4.13	0.25	10.10	4.13	0.22
1A4P4P1F	Parallel (AG)	10.30	4.29	0.20	10.14	4.29	0.18
1A4P4P3F	Parallel (AG)	10.38	4.23	0.23	10.19	4.23	0.20
1A4P4P5F	Parallel (AG)	10.37	4.28	0.21	10.18	4.28	0.19
1A4T3L2F	Transverse (WG)	9.59	4.15	0.16	9.57	4.15	0.15
1A4T3L4F	Transverse (WG)	9.65	4.11	0.17	9.50	4.11	0.15
1A4T3L6F	Transverse (WG)	10.04	4.28	0.17	9.90	4.28	0.16
1A4T2L2F	Transverse (WG)	9.67	4.14	0.17	9.52	4.14	0.15
1A4T2L4F	Transverse (WG)	9.57	4.15	0.15	9.43	4.15	0.14
1A4T2L6F	Transverse (WG)	9.53	4.15	0.15	9.37	4.15	0.13
1B2P1PIF	Parallel (AG)	9.77	4.16	0.18	9.61	4.16	0.15
1B2P1P3F	Parallel (AG)	10.04	4.27	0.18	9.85	4.27	0.15
1B2P1P5F	Parallel (AG)	9.48	4.09	0.16	9.36	4.09	0.14
1B2P4P1F	Parallel (AG)	9.68	4.11	0.18	9.52	4.11	0.16
1B2P4P3F	Parallel (AG)	9.61	4.12	0.17	9.45	4.12	0.15
1B2P4P5F	Parallel (AG)	9.72	4.12	0.18	9.55	4.12	0.16

Table A.10. 2114 graphite Poisson's ratio (by fundamental frequency method) measured on compressive strength specimen in the "Upright" and "Flat" test orientations (continued)

Specimen number	Grain orientation	Upright-Young's modulus E	Shear modulus, g	(Upright) Poisson's ratio, μ	Flat-Young's modulus, E	Shear modulus, g	(Flat) Poisson's ratio, μ
		GPa	GPa		GPa	GPa	
1B2T2L2F	Transverse (WG)	10.37	4.17	0.24	10.17	4.17	0.22
1B2T2L4F	Transverse (WG)	10.30	4.11	0.25	10.11	4.11	0.23
1B2T2L6F	Transverse (WG)	10.40	4.30	0.21	10.22	4.30	0.19
1B2T3L2F	Transverse (WG)	10.53	4.29	0.23	10.33	4.29	0.20
1B2T3L4F	Transverse (WG)	10.37	4.21	0.23	10.15	4.21	0.21
1B2T3L6F	Transverse (WG)	10.22	4.11	0.24	10.04	4.11	0.22
1B3P1P1F	Parallel (AG)	9.97	4.30	0.16	9.85	4.30	0.15
1B3P1P3F	Parallel (AG)	10.11	4.37	0.16	9.98	4.37	0.14
1B3P1P5F	Parallel (AG)	10.32	4.36	0.18	10.17	4.36	0.17
1B3P4P1F	Parallel (AG)	9.50	4.07	0.17	9.34	4.07	0.15
1B3P4P3F	Parallel (AG)	9.68	4.15	0.17	9.53	4.15	0.15
1B3P4P5F	Parallel (AG)	9.90	4.20	0.18	9.73	4.20	0.16
1B3T2L2F	Transverse (WG)	10.92	4.34	0.26	10.68	4.34	0.23
1B3T2L4F	Transverse (WG)	10.69	4.15	0.29	10.47	4.15	0.26
1B3T2L6F	Transverse (WG)	10.43	4.28	0.22	10.25	4.28	0.20
1B3T3L2F	Transverse (WG)	10.46	4.22	0.24	10.26	4.22	0.22
1B3T3L4F	Transverse (WG)	10.69	4.27	0.25	10.48	4.27	0.23
1B3T3L6F	Transverse (WG)	10.77	4.28	0.26	10.54	4.28	0.23
5A1P1P1F	Parallel (AG)	10.15	4.21	0.21	9.98	4.21	0.19
5A1P1P3F	Parallel (AG)	10.21	4.23	0.21	10.03	4.23	0.19
5A1P1P5FR	Parallel (AG)	10.27	4.24	0.21	10.09	4.24	0.19
5A1P4P1F	Parallel (AG)	10.09	4.21	0.20	9.88	4.21	0.17
5A1P4P3F	Parallel (AG)	10.09	4.20	0.20	9.92	4.20	0.18
5A1P4P5F	Parallel (AG)	10.04	4.20	0.20	9.87	4.20	0.18
5A1T2L2F	Transverse (WG)	10.61	4.30	0.23	10.41	4.30	0.21
5A1T2L4F	Transverse (WG)	10.60	4.29	0.24	10.44	4.29	0.22
5A1T2L6F	Transverse (WG)	10.51	4.28	0.23	10.34	4.28	0.21
5A1T3L2FR	Transverse (WG)	10.52	4.27	0.23	10.32	4.27	0.21

Table A.10. 2114 graphite Poisson's ratio (by fundamental frequency method) measured on compressive strength specimen in the "Upright" and "Flat" test orientations (continued)

Specimen number	Grain orientation	Upright-Young's modulus E	Shear modulus, g	(Upright) Poisson's ratio, μ	Flat-Young's modulus, E	Shear modulus, g	(Flat) Poisson's ratio, μ
		GPa	GPa		GPa	GPa	
5A1T3L4F	Transverse (WG)	10.53	4.25	0.24	10.35	4.25	0.22
5A1T3L6F	Transverse (WG)	10.69	4.31	0.24	10.47	4.31	0.22
5B3P1P1F	Parallel (AG)	10.48	4.24	0.23	10.29	4.24	0.21
5B3P1P3F	Parallel (AG)	10.49	4.31	0.22	10.32	4.31	0.20
5B3P1P5F	Parallel (AG)	10.47	4.29	0.22	10.29	4.29	0.20
5B3P4P1F	Parallel (AG)	10.62	4.30	0.23	10.40	4.30	0.21
5B3P4P3F	Parallel (AG)	10.61	4.34	0.22	10.41	4.34	0.20
5B3P4P5FR	Parallel (AG)	10.46	4.29	0.22	10.31	4.29	0.20
5B3T2L2FR	Transverse (WG)	10.37	4.28	0.21	10.18	4.28	0.19
5B3T2L4F	Transverse (WG)	10.27	4.25	0.21	10.08	4.25	0.19
5B3T2L6F	Transverse (WG)	10.32	4.26	0.21	10.14	4.26	0.19
5B3T3L2F	Transverse (WG)	10.23	4.25	0.20	10.06	4.25	0.18
5B3T3L4F	Transverse (WG)	10.37	4.24	0.22	10.10	4.24	0.19
5B3T3L6F	Transverse (WG)	10.25	4.24	0.21	10.06	4.24	0.19

Table A.11. Graphite grade 2114 Poisson's ratio (by fundamental frequency method) measured on compressive strength specimen in the "Flat" test orientations sorted by filler particle (grain) orientation

Specimen number	Grain orientation	Flat-Young's modulus, E	Shear modulus, g	(Flat) Poisson's ratio, μ	Specimen number	Grain orientation	Flat-Young's modulus, E	Shear modulus, g	(Flat) Poisson's ratio, μ
		GPa	GPa				GPa	GPa	
1A1P1P1F	Parallel (AG)	9.48	4.12	0.15	1A1T2L2F	Transverse (WG)	10.14	4.17	0.22
1A1P1P3F	Parallel (AG)	9.58	4.10	0.17	1A1T2L4F	Transverse (WG)	10.01	4.19	0.19
1A1P1P5F	Parallel (AG)	9.74	4.19	0.16	1A1T2L6F	Transverse (WG)	9.94	4.22	0.18
1A1P4P1F	Parallel (AG)	9.78	4.28	0.14	1AIT3L2F	Transverse (WG)	10.28	4.25	0.21
1A1P4P3F	Parallel (AG)	9.90	4.30	0.15	1AIT3L4F	Transverse (WG)	10.41	4.31	0.21
1A1P4P5F	Parallel (AG)	10.00	4.27	0.17	1AIT3L6F	Transverse (WG)	10.28	4.28	0.20
1A4P1P1F	Parallel (AG)	10.19	4.26	0.20	1A4T3L2F	Transverse (WG)	9.57	4.15	0.15
1A4P1P3F	Parallel (AG)	10.11	4.21	0.20	1A4T3L4F	Transverse (WG)	9.50	4.11	0.15
1A4P1P5F	Parallel (AG)	10.10	4.13	0.22	1A4T3L6F	Transverse (WG)	9.90	4.28	0.16
1A4P4P1F	Parallel (AG)	10.14	4.29	0.18	1A4T2L2F	Transverse (WG)	9.52	4.14	0.15
1A4P4P3F	Parallel (AG)	10.19	4.23	0.20	1A4T2L4F	Transverse (WG)	9.43	4.15	0.14
1A4P4P5F	Parallel (AG)	10.18	4.28	0.19	1A4T2L6F	Transverse (WG)	9.37	4.15	0.13
1B2P1PIF	Parallel (AG)	9.61	4.16	0.15	1B2T2L2F	Transverse (WG)	10.17	4.17	0.22
1B2P1P3F	Parallel (AG)	9.85	4.27	0.15	1B2T2L4F	Transverse (WG)	10.11	4.11	0.23
1B2P1P5F	Parallel (AG)	9.36	4.09	0.14	1B2T2L6F	Transverse (WG)	10.22	4.30	0.19
1B2P4P1F	Parallel (AG)	9.52	4.11	0.16	1B2T3L2F	Transverse (WG)	10.33	4.29	0.20
1B2P4P3F	Parallel (AG)	9.45	4.12	0.15	1B2T3L4F	Transverse (WG)	10.15	4.21	0.21
1B2P4P5F	Parallel (AG)	9.55	4.12	0.16	1B2T3L6F	Transverse (WG)	10.04	4.11	0.22
1B3P1P1F	Parallel (AG)	9.85	4.30	0.15	1B3T2L2F	Transverse (WG)	10.68	4.34	0.23
1B3P1P3F	Parallel (AG)	9.98	4.37	0.14	1B3T2L4F	Transverse (WG)	10.47	4.15	0.26

Table A.11. Graphite grade 2114 Poisson's ratio (by fundamental frequency method) measured on compressive strength specimen in the "Flat" test orientations sorted by filler particle (grain) orientation (continued)

Specimen number	Grain orientation	Flat-Young's modulus, E	Shear modulus, g	(Flat) Poisson's ratio, μ	Specimen number	Grain orientation	Flat-Young's modulus, E	Shear modulus, g	(Flat) Poisson's ratio, μ
		GPa	GPa				GPa	GPa	
1B3P1P5F	Parallel (AG)	10.17	4.36	0.17	1B3T2L6F	Transverse (WG)	10.25	4.28	0.20
1B3P4P1F	Parallel (AG)	9.34	4.07	0.15	1B3T3L2F	Transverse (WG)	10.26	4.22	0.22
1B3P4P3F	Parallel (AG)	9.53	4.15	0.15	1B3T3L4F	Transverse (WG)	10.48	4.27	0.23
1B3P4P5F	Parallel (AG)	9.73	4.20	0.16	1B3T3L6F	Transverse (WG)	10.54	4.28	0.23
5A1P1P1F	Parallel (AG)	9.98	4.21	0.19	5A1T2L2F	Transverse (WG)	10.41	4.30	0.21
5A1P1P3F	Parallel (AG)	10.03	4.23	0.19	5A1T2L4F	Transverse (WG)	10.44	4.29	0.22
5A1P1P5FR	Parallel (AG)	10.09	4.24	0.19	5A1T2L6F	Transverse (WG)	10.34	4.28	0.21
5A1P4P1F	Parallel (AG)	9.88	4.21	0.17	5A1T3L2FR	Transverse (WG)	10.32	4.27	0.21
5A1P4P3F	Parallel (AG)	9.92	4.20	0.18	5A1T3L4F	Transverse (WG)	10.35	4.25	0.22
5A1P4P5F	Parallel (AG)	9.87	4.20	0.18	5A1T3L6F	Transverse (WG)	10.47	4.31	0.22
5B3P1P1F	Parallel (AG)	10.29	4.24	0.21	5B3T2L2FR	Transverse (WG)	10.18	4.28	0.19
5B3P1P3F	Parallel (AG)	10.32	4.31	0.20	5B3T2L4F	Transverse (WG)	10.08	4.25	0.19
5B3P1P5F	Parallel (AG)	10.29	4.29	0.20	5B3T2L6F	Transverse (WG)	10.14	4.26	0.19
5B3P4P1F	Parallel (AG)	10.40	4.30	0.21	5B3T3L2F	Transverse (WG)	10.06	4.25	0.18
5B3P4P3F	Parallel (AG)	10.41	4.34	0.20	5B3T3L4F	Transverse (WG)	10.10	4.24	0.19
5B3P4P5FR	Parallel (AG)	10.31	4.29	0.20	5B3T3L6F	Transverse (WG)	10.06	4.24	0.19

Table A.12. Graphite grade 2114 Poisson's ratio (by fundamental frequency method) measured on compressive strength specimen in the "Flat" test orientations sorted by in-billet location (billet end = specimen numbers beginning with 1: billet center = specimen numbers beginning with 5) (With-grain specimens only)

Specimen number	Grain orientation	Flat-Young's modulus, E	Shear modulus, g	(Flat) Poisson's ratio, μ	Specimen number	Grain orientation	Flat-Young's modulus, E	Shear modulus, g	(Flat) Poisson's ratio, μ
		GPa	GPa				GPa	GPa	
1A1T2L2F	Transverse (WG)	10.14	4.17	0.22	5A1T2L2F	Transverse (WG)	10.41	4.30	0.21
1A1T2L4F	Transverse (WG)	10.01	4.19	0.19	5A1T2L4F	Transverse (WG)	10.44	4.29	0.22
1A1T2L6F	Transverse (WG)	9.94	4.22	0.18	5A1T2L6F	Transverse (WG)	10.34	4.28	0.21
1AIT3L2F	Transverse (WG)	10.28	4.25	0.21	5A1T3L2FR	Transverse (WG)	10.32	4.27	0.21
1AIT3L4F	Transverse (WG)	10.41	4.31	0.21	5A1T3L4F	Transverse (WG)	10.35	4.25	0.22
1AIT3L6F	Transverse (WG)	10.28	4.28	0.20	5A1T3L6F	Transverse (WG)	10.47	4.31	0.22
1A4T3L2F	Transverse (WG)	9.57	4.15	0.15	5B3T2L2FR	Transverse (WG)	10.18	4.28	0.19
1A4T3L4F	Transverse (WG)	9.50	4.11	0.15	5B3T2L4F	Transverse (WG)	10.08	4.25	0.19
1A4T3L6F	Transverse (WG)	9.90	4.28	0.16	5B3T2L6F	Transverse (WG)	10.14	4.26	0.19
1A4T2L2F	Transverse (WG)	9.52	4.14	0.15	5B3T3L2F	Transverse (WG)	10.06	4.25	0.18
1A4T2L4F	Transverse (WG)	9.43	4.15	0.14	5B3T3L4F	Transverse (WG)	10.10	4.24	0.19
1A4T2L6F	Transverse (WG)	9.37	4.15	0.13	5B3T3L6F	Transverse (WG)	10.06	4.24	0.19
1B2T2L2F	Transverse (WG)	10.17	4.17	0.22					
1B2T2L4F	Transverse (WG)	10.11	4.11	0.23					
1B2T2L6F	Transverse (WG)	10.22	4.30	0.19					
1B2T3L2F	Transverse (WG)	10.33	4.29	0.20					
1B2T3L4F	Transverse (WG)	10.15	4.21	0.21					
1B2T3L6F	Transverse (WG)	10.04	4.11	0.22					

Table A.12. Graphite grade 2114 Poisson's ratio (by fundamental frequency method) measured on compressive strength specimen in the "Flat" test orientations sorted by in-billet location (billet end = specimen numbers beginning with 1: billet center = specimen numbers beginning with 5) (With-grain specimens only) (continued)

Specimen number	Grain orientation	Flat-Young's modulus, E	Shear modulus, g	(Flat) Poisson's ratio, μ	Specimen number	Grain orientation	Flat-Young's modulus, E	Shear modulus, g	(Flat) Poisson's ratio, μ
		GPa	GPa				GPa	GPa	
1B3T2L2F	Transverse (WG)	10.68	4.34	0.23					
1B3T2L4F	Transverse (WG)	10.47	4.15	0.26					
1B3T2L6F	Transverse (WG)	10.25	4.28	0.20					
1B3T3L2F	Transverse (WG)	10.26	4.22	0.22					
1B3T3L4F	Transverse (WG)	10.48	4.27	0.23					
1B3T3L6F	Transverse (WG)	10.54	4.28	0.23					

Table A.13. Sonic velocity (TOF) derived elastic constants for graphite grade 2114 billet 116310

Specimen number	Grain orientation	Density, ρ (Kg/m^3)	Sonic velocities, υ [m/s]		ELASTIC CONSTANTS			
			Longitudinal	Average shear velocity	Elastic modulus, [Pa]	Shear modulus, [Pa]	Poisson's ratio	Poisson's corrected elastic modulus, [Pa]
					$E\rho\upsilon_l^2$	$G\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
1A1P1P1F	Parallel (AG)	1816.3	2420.9	1.509E+03	1.06448E+10	4.137E+09	1.822E-01	9.781E+09
1A1P1P3F	Parallel (AG)	1815.0	2423.5	1.508E+03	1.06603E+10	4.129E+09	1.838E-01	9.777E+09
1A1P1P5F	Parallel (AG)	1818.9	2436.4	1.517E+03	1.07973E+10	4.187E+09	1.832E-01	9.909E+09
1A1T2L2F	Transverse (WG)	1815.1	2440.5	1.526E+03	1.08107E+10	4.224E+09	1.793E-01	9.964E+09
1A1T2L4F	Transverse (WG)	1815.9	2503.8	1.522E+03	1.13835E+10	4.204E+09	2.072E-01	1.015E+10
1A1T2L6F	Transverse (WG)	1817.0	2489.7	1.535E+03	1.12632E+10	4.283E+09	1.932E-01	1.022E+10
1AIT3L2F	Transverse (WG)	1816.3	2528.7	1.539E+03	1.16143E+10	4.302E+09	2.058E-01	1.038E+10
1AIT3L4F	Transverse (WG)	1817.5	2538.5	1.530E+03	1.17120E+10	4.253E+09	2.149E-01	1.033E+10
1AIT3L6F	Transverse (WG)	1820.0	2528.9	1.526E+03	1.16390E+10	4.241E+09	2.134E-01	1.029E+10
1A1P4P1F	Parallel (AG)	1819.4	2457.5	1.523E+03	1.09879E+10	4.221E+09	1.881E-01	1.003E+10
1A1P4P3F	Parallel (AG)	1820.6	2461.0	1.528E+03	1.10266E+10	4.249E+09	1.865E-01	1.008E+10
1A1P4P5F	Parallel (AG)	1822.4	2479.1	1.534E+03	1.12001E+10	4.288E+09	1.899E-01	1.020E+10
1A4P1P1F	Parallel (AG)	1817.3	2498.0	1.546E+03	1.13405E+10	4.345E+09	1.894E-01	1.034E+10
1A4P1P3F	Parallel (AG)	1817.3	2498.0	1.536E+03	1.13403E+10	4.287E+09	1.962E-01	1.025E+10
1A4P1P5F	Parallel (AG)	1818.0	2496.5	1.523E+03	1.13304E+10	4.214E+09	2.039E-01	1.015E+10
1A4P4P1F	Parallel (AG)	1816.3	2498.9	1.539E+03	1.13415E+10	4.299E+09	1.948E-01	1.027E+10
1A4P4P3F	Parallel (AG)	1815.9	2510.8	1.537E+03	1.14476E+10	4.290E+09	2.003E-01	1.030E+10
1A4P4P5F	Parallel (AG)	1818.3	2508.0	1.523E+03	1.14373E+10	4.220E+09	2.077E-01	1.019E+10
1A4T3L2F	Transverse (WG)	1817.5	2429.2	1.506E+03	1.07253E+10	4.125E+09	1.876E-01	9.796E+09

Table A.13. Sonic velocity (TOF) derived elastic constants for graphite grade 2114 billet 116310 (continued)

Specimen number	Grain orientation	Density, ρ (Kg/m^3)	Sonic velocities, υ [m/s]		ELASTIC CONSTANTS			
			Longitudinal	Average shear velocity	Elastic modulus, [Pa]	Shear modulus, [Pa]	Poisson's ratio	Poisson's corrected elastic modulus, [Pa]
1A4T3L4F	Transverse (WG)	1816.2	2423.7	1.508E+03	1.06690E+10	4.129E+09	1.844E-01	9.780E+09
1A4T3L6F	Transverse (WG)	1822.5	2476.3	1.526E+03	1.11757E+10	4.244E+09	1.938E-01	1.013E+10
1A4T2L2F	Transverse (WG)	1818.9	2429.8	1.511E+03	1.07389E+10	4.151E+09	1.849E-01	9.838E+09
1A4T2L4F	Transverse (WG)	1816.9	2412.9	1.504E+03	1.05782E+10	4.108E+09	1.826E-01	9.716E+09
1A4T2L6F	Transverse (WG)	1816.4	2404.0	1.499E+03	1.04971E+10	4.079E+09	1.822E-01	9.644E+09
1B2P1PIF	Parallel (AG)	1819.7	2440.2	1.517E+03	1.08360E+10	4.188E+09	1.851E-01	9.925E+09
1B2P1P3F	Parallel (AG)	1827.1	2478.3	1.530E+03	1.12216E+10	4.279E+09	1.918E-01	1.020E+10
1B2P1P5F	Parallel (AG)	1816.4	2411.8	1.515E+03	1.05656E+10	4.167E+09	1.744E-01	9.787E+09
1B2P4P1F	Parallel (AG)	1820.1	2415.9	1.507E+03	1.06233E+10	4.133E+09	1.816E-01	9.767E+09
1B2P4P3F	Parallel (AG)	1817.8	2409.9	1.509E+03	1.05568E+10	4.138E+09	1.776E-01	9.747E+09
1B2P4P5F	Parallel (AG)	1819.4	2426.5	1.508E+03	1.07130E+10	4.138E+09	1.854E-01	9.809E+09
1B2T2L2F	Transverse (WG)	1818.2	2505.7	1.533E+03	1.14156E+10	4.271E+09	2.011E-01	1.026E+10
1B2T2L4F	Transverse (WG)	1813.0	2501.0	1.539E+03	1.13400E+10	4.293E+09	1.954E-01	1.026E+10
1B2T2L6F	Transverse (WG)	1819.5	2505.2	1.534E+03	1.14189E+10	4.279E+09	2.003E-01	1.027E+10
1B2T3L2F	Transverse (WG)	1820.1	2508.2	1.546E+03	1.14507E+10	4.351E+09	1.936E-01	1.039E+10
1B2T3L4F	Transverse (WG)	1820.6	2503.9	1.522E+03	1.14144E+10	4.219E+09	2.069E-01	1.018E+10
1B2T3L6F	Transverse (WG)	1816.0	2491.2	1.519E+03	1.12701E+10	4.190E+09	2.041E-01	1.009E+10
1B3P1P1F	Parallel (AG)	1828.6	2447.7	1.530E+03	1.09559E+10	4.282E+09	1.792E-01	1.010E+10
1B3P1P3F	Parallel (AG)	1830.2	2474.8	1.543E+03	1.12097E+10	4.356E+09	1.823E-01	1.030E+10
1B3P1P5F	Parallel (AG)	1831.6	2493.3	1.543E+03	1.13860E+10	4.360E+09	1.897E-01	1.037E+10

Table A.13. Sonic velocity (TOF) derived elastic constants for graphite grade 2114 billet 116310 (continued)

Specimen number	Grain orientation	Density, ρ (Kg/m^3)	Sonic velocities, υ [m/s]		ELASTIC CONSTANTS			
			Longitudinal	Average shear velocity	Elastic modulus, [Pa]	Shear modulus, [Pa]	Poisson's ratio	Poisson's corrected elastic modulus, [Pa]
1B3P4P1F	Parallel (AG)	1815.2	2444.6	1.504E+03	1.08472E+10	4.106E+09	1.954E-01	9.817E+09
1B3P4P3F	Parallel (AG)	1818.9	2418.1	1.519E+03	1.06352E+10	4.194E+09	1.744E-01	9.852E+09
1B3P4P5F	Parallel (AG)	1821.4	2453.6	1.521E+03	1.09652E+10	4.214E+09	1.879E-01	1.001E+10
1B3T2L2F	Transverse (WG)	1826.5	2557.3	1.559E+03	1.19454E+10	4.438E+09	2.045E-01	1.069E+10
1B3T2L4F	Transverse (WG)	1824.3	2536.9	1.559E+03	1.17405E+10	4.436E+09	1.964E-01	1.061E+10
1B3T2L6F	Transverse (WG)	1820.2	2517.9	1.545E+03	1.15400E+10	4.347E+09	1.978E-01	1.041E+10
1B3T3L2F	Transverse (WG)	1820.3	2519.9	1.542E+03	1.15590E+10	4.330E+09	2.005E-01	1.040E+10
1B3T3L4F	Transverse (WG)	1822.4	2540.4	1.562E+03	1.17615E+10	4.445E+09	1.962E-01	1.063E+10
1B3T3L6F	Transverse (WG)	1823.6	2544.8	1.547E+03	1.18092E+10	4.365E+09	2.069E-01	1.053E+10
5A1P1P1F	Parallel (AG)	1816.6	2493.8	1.525E+03	1.12970E+10	4.226E+09	2.011E-01	1.015E+10
5A1P1P3F	Parallel (AG)	1817.1	2503.1	1.532E+03	1.13852E+10	4.266E+09	2.004E-01	1.024E+10
5A1P1P5FR	Parallel (AG)	1815.5	2515.3	1.534E+03	1.14861E+10	4.272E+09	2.039E-01	1.029E+10
5A1P4P1F	Parallel (AG)	1816.0	2474.9	1.527E+03	1.11235E+10	4.236E+09	1.925E-01	1.010E+10
5A1P4P3F	Parallel (AG)	1816.5	2476.5	1.528E+03	1.11407E+10	4.241E+09	1.927E-01	1.012E+10
5A1P4P5F	Parallel (AG)	1814.7	2482.6	1.526E+03	1.11845E+10	4.229E+09	1.960E-01	1.012E+10
5A1T2L2F	Transverse (WG)	1816.2	2548.7	1.541E+03	1.17973E+10	4.312E+09	2.120E-01	1.045E+10
5A1T2L4F	Transverse (WG)	1815.2	2546.5	1.544E+03	1.17703E+10	4.326E+09	2.095E-01	1.046E+10
5A1T2L6F	Transverse (WG)	1816.7	2538.0	1.536E+03	1.17017E+10	4.289E+09	2.107E-01	1.038E+10
5A1T3L2FR	Transverse (WG)	1816.3	2533.9	1.537E+03	1.16617E+10	4.292E+09	2.088E-01	1.038E+10

Table A.13. Sonic velocity (TOF) derived elastic constants for graphite grade 2114 billet 116310 (continued)

Specimen number	Grain orientation	Density, ρ (Kg/m^3)	Sonic velocities, υ [m/s]		ELASTIC CONSTANTS			
			Longitudinal	Average shear velocity	Elastic modulus, [Pa]	Shear modulus, [Pa]	Poisson's ratio	Poisson's corrected elastic modulus, [Pa]
5A1T3L4F	Transverse (WG)	1817.7	2536.8	1.528E+03	1.16976E+10	4.242E+09	2.155E-01	1.031E+10
5A1T3L6F	Transverse (WG)	1819.0	2554.1	1.549E+03	1.18655E+10	4.366E+09	2.089E-01	1.056E+10
5B3P1P1F	Parallel (AG)	1820.0	2524.4	1.528E+03	1.15982E+10	4.248E+09	2.110E-01	1.029E+10
5B3P1P3F	Parallel (AG)	1820.0	2527.7	1.547E+03	1.16285E+10	4.354E+09	2.007E-01	1.046E+10
5B3P1P5F	Parallel (AG)	1820.0	2521.5	1.543E+03	1.15717E+10	4.335E+09	2.005E-01	1.041E+10
5B3P4P1F	Parallel (AG)	1822.9	2548.1	1.546E+03	1.18355E+10	4.355E+09	2.089E-01	1.053E+10
5B3P4P3F	Parallel (AG)	1823.5	2543.2	1.551E+03	1.17934E+10	4.389E+09	2.036E-01	1.057E+10
5B3P4P5FR	Parallel (AG)	1815.8	2538.4	1.549E+03	1.17001E+10	4.357E+09	2.034E-01	1.049E+10
5B3T2L2FR	Transverse (WG)	1825.5	2515.9	1.537E+03	1.15551E+10	4.313E+09	2.022E-01	1.037E+10
5B3T2L4F	Transverse (WG)	1820.2	2509.1	1.534E+03	1.14591E+10	4.284E+09	2.015E-01	1.029E+10
5B3T2L6F	Transverse (WG)	1820.2	2510.9	1.535E+03	1.14758E+10	4.290E+09	2.014E-01	1.031E+10
5B3T3L2F	Transverse (WG)	1819.2	2501.2	1.535E+03	1.13813E+10	4.288E+09	1.977E-01	1.027E+10
5B3T3L4F	Transverse (WG)	1820.7	2502.7	1.527E+03	1.14042E+10	4.246E+09	2.034E-01	1.022E+10
5B3T3L6F	Transverse (WG)	1824.9	2498.7	1.532E+03	1.13935E+10	4.285E+09	1.986E-01	1.027E+10

Table A.14. Sonic velocity (TOF) derived elastic constants for graphite grade 2114 billet 116310 in the AG orientation

Specimen number	Grain orientation	Density, ρ (Kg/m3)	Sonic velocities, u [m/s]		ELASTIC CONSTANTS			
			Longitudinal	Average shear velocity	Elastic modulus, [Pa]	Shear modulus, [Pa]	Poisson's ratio	Poisson's corrected elastic modulus, [Pa]
					$E\rho\upsilon_l^2$	$G\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
1A1P1P1F	Parallel (AG)	1816	2420.86	1509.11	1.06E+10	4.14E+09	0.18	9.78E+09
1A1P1P3F	Parallel (AG)	1815	2423.51	1508.36	1.07E+10	4.13E+09	0.18	9.78E+09
1A1P1P5F	Parallel (AG)	1819	2436.42	1517.28	1.08E+10	4.19E+09	0.18	9.91E+09
1A1P4P1F	Parallel (AG)	1819	2457.49	1523.15	1.10E+10	4.22E+09	0.19	1.00E+10
1A1P4P3F	Parallel (AG)	1821	2460.99	1527.68	1.10E+10	4.25E+09	0.19	1.01E+10
1A1P4P5F	Parallel (AG)	1822	2479.05	1533.84	1.12E+10	4.29E+09	0.19	1.02E+10
1A4P1P1F	Parallel (AG)	1817	2498.03	1546.26	1.13E+10	4.35E+09	0.19	1.03E+10
1A4P1P3F	Parallel (AG)	1817	2498.03	1535.82	1.13E+10	4.29E+09	0.20	1.03E+10
1A4P1P5F	Parallel (AG)	1818	2496.48	1522.54	1.13E+10	4.21E+09	0.20	1.01E+10
1A4P4P1F	Parallel (AG)	1816	2498.88	1538.54	1.13E+10	4.30E+09	0.19	1.03E+10
1A4P4P3F	Parallel (AG)	1816	2510.79	1537.12	1.14E+10	4.29E+09	0.20	1.03E+10
1A4P4P5F	Parallel (AG)	1818	2507.98	1523.35	1.14E+10	4.22E+09	0.21	1.02E+10
1B2P1PIF	Parallel (AG)	1820	2440.24	1516.98	1.08E+10	4.19E+09	0.19	9.93E+09
1B2P1P3F	Parallel (AG)	1827	2478.29	1530.43	1.12E+10	4.28E+09	0.19	1.02E+10
1B2P1P5F	Parallel (AG)	1816	2411.79	1514.56	1.06E+10	4.17E+09	0.17	9.79E+09
1B2P4P1F	Parallel (AG)	1820	2415.90	1506.92	1.06E+10	4.13E+09	0.18	9.77E+09
1B2P4P3F	Parallel (AG)	1818	2409.87	1508.81	1.06E+10	4.14E+09	0.18	9.75E+09
1B2P4P5F	Parallel (AG)	1819	2426.55	1508.02	1.07E+10	4.14E+09	0.19	9.81E+09

Table A.14. Sonic velocity (TOF) derived elastic constants for graphite grade 2114 billet 116310 in the AG orientation (continued)

Specimen number	Grain orientation	Density, ρ (Kg/m3)	Sonic velocities, u [m/s]		ELASTIC CONSTANTS			
			Longitudinal	Average shear velocity	Elastic modulus, [Pa]	Shear modulus, [Pa]	Poisson's ratio	Poisson's corrected elastic modulus, [Pa]
					$E\rho\upsilon_l^2$	$G\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
1B3P1P1F	Parallel (AG)	1829	2447.70	1530.23	1.10E+10	4.28E+09	0.18	1.01E+10
1B3P1P3F	Parallel (AG)	1830	2474.82	1542.68	1.12E+10	4.36E+09	0.18	1.03E+10
1B3P1P5F	Parallel (AG)	1832	2493.29	1542.84	1.14E+10	4.36E+09	0.19	1.04E+10
1B3P4P1F	Parallel (AG)	1815	2444.56	1504.05	1.08E+10	4.11E+09	0.20	9.82E+09
1B3P4P3F	Parallel (AG)	1819	2418.10	1518.54	1.06E+10	4.19E+09	0.17	9.85E+09
1B3P4P5F	Parallel (AG)	1821	2453.62	1521.01	1.10E+10	4.21E+09	0.19	1.00E+10
5A1P1P1F	Parallel (AG)	1817	2493.78	1525.33	1.13E+10	4.23E+09	0.20	1.02E+10
5A1P1P3F	Parallel (AG)	1817	2503.12	1532.17	1.14E+10	4.27E+09	0.20	1.02E+10
5A1P1P5FR	Parallel (AG)	1815	2515.29	1534.02	1.15E+10	4.27E+09	0.20	1.03E+10
5A1P4P1F	Parallel (AG)	1816	2474.91	1527.26	1.11E+10	4.24E+09	0.19	1.01E+10
5A1P4P3F	Parallel (AG)	1816	2476.51	1527.98	1.11E+10	4.24E+09	0.19	1.01E+10
5A1P4P5F	Parallel (AG)	1815	2482.57	1526.50	1.12E+10	4.23E+09	0.20	1.01E+10
5B3P1P1F	Parallel (AG)	1820	2524.44	1527.77	1.16E+10	4.25E+09	0.21	1.03E+10
5B3P1P3F	Parallel (AG)	1820	2527.69	1546.78	1.16E+10	4.35E+09	0.20	1.05E+10
5B3P1P5F	Parallel (AG)	1820	2521.52	1543.25	1.16E+10	4.33E+09	0.20	1.04E+10
5B3P4P1F	Parallel (AG)	1823	2548.08	1545.70	1.18E+10	4.36E+09	0.21	1.05E+10
5B3P4P3F	Parallel (AG)	1823	2543.16	1551.43	1.18E+10	4.39E+09	0.20	1.06E+10
5B3P4P5FR	Parallel (AG)	1816	2538.40	1548.95	1.17E+10	4.36E+09	0.20	1.05E+10

Table A.15. Sonic velocity (TOF) derived elastic constants for graphite grade 2114 billet 116310 in the WG orientation

Specimen number	Grain orientation	Density, ρ (Kg/m3)	Sonic velocities, u [m/s]		ELASTIC CONSTANTS			
			Longitudinal	Average shear velocity	Elastic modulus, [Pa]	Shear modulus, [Pa]	Poisson's ratio	Poisson's corrected elastic modulus, [Pa]
					$E\rho\upsilon_l^2$	$G\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
1A1T2L2F	Transverse (WG)	1815	2440.52	1525.57	1.08E+10	4.22E+09	0.18	9.96E+09
1A1T2L4F	Transverse (WG)	1816	2503.78	1521.52	1.14E+10	4.20E+09	0.21	1.01E+10
1A1T2L6F	Transverse (WG)	1817	2489.71	1535.25	1.13E+10	4.28E+09	0.19	1.02E+10
1AIT3L2F	Transverse (WG)	1816	2528.70	1539.08	1.16E+10	4.30E+09	0.21	1.04E+10
1AIT3L4F	Transverse (WG)	1818	2538.47	1529.76	1.17E+10	4.25E+09	0.21	1.03E+10
1AIT3L6F	Transverse (WG)	1820	2528.87	1526.50	1.16E+10	4.24E+09	0.21	1.03E+10
1A4T3L2F	Transverse (WG)	1818	2429.21	1506.43	1.07E+10	4.12E+09	0.19	9.80E+09
1A4T3L4F	Transverse (WG)	1816	2423.72	1507.72	1.07E+10	4.13E+09	0.18	9.78E+09
1A4T3L6F	Transverse (WG)	1823	2476.28	1526.04	1.12E+10	4.24E+09	0.19	1.01E+10
1A4T2L2F	Transverse (WG)	1819	2429.80	1510.71	1.07E+10	4.15E+09	0.18	9.84E+09
1A4T2L4F	Transverse (WG)	1817	2412.92	1503.65	1.06E+10	4.11E+09	0.18	9.72E+09
1A4T2L6F	Transverse (WG)	1816	2403.96	1498.52	1.05E+10	4.08E+09	0.18	9.64E+09
1B2T2L2F	Transverse (WG)	1818	2505.67	1532.58	1.14E+10	4.27E+09	0.20	1.03E+10
1B2T2L4F	Transverse (WG)	1813	2500.98	1538.83	1.13E+10	4.29E+09	0.20	1.03E+10
1B2T2L6F	Transverse (WG)	1819	2505.18	1533.62	1.14E+10	4.28E+09	0.20	1.03E+10
1B2T3L2F	Transverse (WG)	1820	2508.23	1546.07	1.15E+10	4.35E+09	0.19	1.04E+10
1B2T3L4F	Transverse (WG)	1821	2503.94	1522.23	1.14E+10	4.22E+09	0.21	1.02E+10
1B2T3L6F	Transverse (WG)	1816	2491.17	1518.90	1.13E+10	4.19E+09	0.20	1.01E+10

Table A.15. Sonic velocity (TOF) derived elastic constants for graphite grade 2114 billet 116310 in the WG orientation (continued)

Specimen number	Grain orientation	Density, ρ (Kg/m3)	Sonic velocities, u [m/s]		ELASTIC CONSTANTS			
			Longitudinal	Average shear velocity	Elastic modulus, [Pa]	Shear modulus, [Pa]	Poisson's ratio	Poisson's corrected elastic modulus, [Pa]
					$E\rho\upsilon_l^2$	$G\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
1B3T2L2F	Transverse (WG)	1827	2557.34	1558.69	1.19E+10	4.44E+09	0.20	1.07E+10
1B3T2L4F	Transverse (WG)	1824	2536.87	1559.29	1.17E+10	4.44E+09	0.20	1.06E+10
1B3T2L6F	Transverse (WG)	1820	2517.93	1545.43	1.15E+10	4.35E+09	0.20	1.04E+10
1B3T3L2F	Transverse (WG)	1820	2519.93	1542.26	1.16E+10	4.33E+09	0.20	1.04E+10
1B3T3L4F	Transverse (WG)	1822	2540.42	1561.73	1.18E+10	4.44E+09	0.20	1.06E+10
1B3T3L6F	Transverse (WG)	1824	2544.76	1547.06	1.18E+10	4.36E+09	0.21	1.05E+10
5A1T2L2F	Transverse (WG)	1816	2548.68	1540.86	1.18E+10	4.31E+09	0.21	1.05E+10
5A1T2L4F	Transverse (WG)	1815	2546.46	1543.71	1.18E+10	4.33E+09	0.21	1.05E+10
5A1T2L6F	Transverse (WG)	1817	2537.97	1536.45	1.17E+10	4.29E+09	0.21	1.04E+10
5A1T3L2FR	Transverse (WG)	1816	2533.92	1537.33	1.17E+10	4.29E+09	0.21	1.04E+10
5A1T3L4F	Transverse (WG)	1818	2536.80	1527.72	1.17E+10	4.24E+09	0.22	1.03E+10
5A1T3L6F	Transverse (WG)	1819	2554.06	1549.31	1.19E+10	4.37E+09	0.21	1.06E+10
5B3T2L2FR	Transverse (WG)	1825	2515.93	1537.18	1.16E+10	4.31E+09	0.20	1.04E+10
5B3T2L4F	Transverse (WG)	1820	2509.05	1534.13	1.15E+10	4.28E+09	0.20	1.03E+10
5B3T2L6F	Transverse (WG)	1820	2510.88	1535.27	1.15E+10	4.29E+09	0.20	1.03E+10
5B3T3L2F	Transverse (WG)	1819	2501.23	1535.26	1.14E+10	4.29E+09	0.20	1.03E+10
5B3T3L4F	Transverse (WG)	1821	2502.71	1527.16	1.14E+10	4.25E+09	0.20	1.02E+10
5B3T3L6F	Transverse (WG)	1825	2498.69	1532.32	1.14E+10	4.28E+09	0.20	1.03E+10

Table A.16. Sonic velocity (TOF) derived elastic constants for graphite grade 2114 billet 116310 in the AG orientation sorted by in-billet location

Specimen number	Grain orientation	ELASTIC CONSTANTS			Specimen number	Grain orientation	ELASTIC CONSTANTS			
		Shear modulus, [Pa]	Poisson's ratio	Poisson's corrected elastic modulus, [Pa]			Elastic modulus, [Pa]	Shear modulus, [Pa]	Poisson's ratio	Poisson's corrected elastic modulus, [Pa]
		G=ρυs2	μ=(1-[2(υs/υl)2])/(2-[2(υs/υl)2])	E=ρυl2[(1+μ)(1-2μ)/(1-μ)]			E=ρυl2	G=ρυs2	μ=(1-[2(υs/υl)2])/(2-[2(υs/υl)2])	E=ρυl2[(1+μ)(1-2μ)/(1-μ)]
1A1P1P1F	Parallel (AG)	4.14E+09	0.18	9780508443	5A1P1P1F	Parallel (AG)	1.13E+10	4.23E+09	0.20	1.015E+10
1A1P1P3F	Parallel (AG)	4.13E+09	0.18	9777304153	5A1P1P3F	Parallel (AG)	1.14E+10	4.27E+09	0.20	1.024E+10
1A1P1P5F	Parallel (AG)	4.19E+09	0.18	9909427222	5A1P1P5FR	Parallel (AG)	1.15E+10	4.27E+09	0.20	1.029E+10
1A1P4P1F	Parallel (AG)	4.22E+09	0.19	10030061290	5A1P4P1F	Parallel (AG)	1.11E+10	4.24E+09	0.19	1.01E+10
1A1P4P3F	Parallel (AG)	4.25E+09	0.19	10083267503	5A1P4P3F	Parallel (AG)	1.11E+10	4.24E+09	0.19	1.012E+10
1A1P4P5F	Parallel (AG)	4.29E+09	0.19	10203330013	5A1P4P5F	Parallel (AG)	1.12E+10	4.23E+09	0.20	1.012E+10
1A4P1P1F	Parallel (AG)	4.35E+09	0.19	10336393806	5B3P1P1F	Parallel (AG)	1.16E+10	4.25E+09	0.21	1.029E+10
1A4P1P3F	Parallel (AG)	4.29E+09	0.20	10254728279	5B3P1P3F	Parallel (AG)	1.16E+10	4.35E+09	0.20	1.046E+10
1A4P1P5F	Parallel (AG)	4.21E+09	0.20	10147159704	5B3P1P5F	Parallel (AG)	1.16E+10	4.33E+09	0.20	1.041E+10
1A4P4P1F	Parallel (AG)	4.3E+09	0.19	10273131918	5B3P4P1F	Parallel (AG)	1.18E+10	4.36E+09	0.21	1.053E+10
1A4P4P3F	Parallel (AG)	4.29E+09	0.20	10299436809	5B3P4P3F	Parallel (AG)	1.18E+10	4.39E+09	0.20	1.057E+10
1A4P4P5F	Parallel (AG)	4.22E+09	0.21	10191997598	5B3P4P5FR	Parallel (AG)	1.17E+10	4.36E+09	0.20	1.049E+10
1B2P1PIF	Parallel (AG)	4.19E+09	0.19	9925158989						
1B2P1P3F	Parallel (AG)	4.28E+09	0.19	10200234462						
1B2P1P5F	Parallel (AG)	4.17E+09	0.17	9786843983						
1B2P4P1F	Parallel (AG)	4.13E+09	0.18	9767363696						

Table A.16. Sonic velocity (TOF) derived elastic constants for graphite grade 2114 billet 116310 in the AG orientation sorted by in-billet location (continued)

Specimen number	Grain orientation	ELASTIC CONSTANTS			Specimen number	Grain orientation	ELASTIC CONSTANTS			
		Shear modulus, [Pa]	Poisson’s ratio	Poisson’s corrected elastic modulus, [Pa]			Elastic modulus, [Pa]	Shear modulus, [Pa]	Poisson’s ratio	Poisson’s corrected elastic modulus, [Pa]
		G=ρυs2	μ=(1-[2(υs/υl)2])/(2-[2(υs/υl)2])	E=ρυl2[(1+μ)(1-2μ)/(1-μ)]			E=ρυl2	G=ρυs2	μ=(1-[2(υs/υl)2])/(2-[2(υs/υl)2])	E=ρυl2[(1+μ)(1-2μ)/(1-μ)]
1B2P4P3F	Parallel (AG)	4.14E+09	0.18	9746646049						
1B2P4P5F	Parallel (AG)	4.14E+09	0.19	9809171638						
1B3P1P1F	Parallel (AG)	4.28E+09	0.18	10098642188						
1B3P1P3F	Parallel (AG)	4.36E+09	0.18	10299054603						
1B3P1P5F	Parallel (AG)	4.36E+09	0.19	10374102266						
1B3P4P1F	Parallel (AG)	4.11E+09	0.20	9817302926						
1B3P4P3F	Parallel (AG)	4.19E+09	0.17	9851500129						
1B3P4P5F	Parallel (AG)	4.21E+09	0.19	10011299253						

Table A.17. Sonic velocity (TOF) derived elastic constants for graphite grade 2114 billet 116310 in the WG orientation sorted by in-billet location

Specimen number	Grain orientation	ELASTIC CONSTANTS			Specimen number	Grain orientation	ELASTIC CONSTANTS		
		Shear modulus, [Pa]	**Poisson's ratio**	**Poisson's corrected elastic modulus, [Pa]**			**Shear modulus, [Pa]**	**Poisson's ratio**	**Poisson's corrected elastic modulus, [Pa]**
		$G\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$			$G=\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
1A1T2L2F	Transverse (WG)	4.22E+09	0.18	9.96E+09	5A1T2L2F	Transverse (WG)	4.31E+09	0.21	1.05E+10
1A1T2L4F	Transverse (WG)	4.20E+09	0.21	1.01E+10	5A1T2L4F	Transverse (WG)	4.33E+09	0.21	1.05E+10
1A1T2L6F	Transverse (WG)	4.28E+09	0.19	1.02E+10	5A1T2L6F	Transverse (WG)	4.29E+09	0.21	1.04E+10
1AIT3L2F	Transverse (WG)	4.30E+09	0.21	1.04E+10	5A1T3L2FR	Transverse (WG)	4.29E+09	0.21	1.04E+10
1AIT3L4F	Transverse (WG)	4.25E+09	0.21	1.03E+10	5A1T3L4F	Transverse (WG)	4.24E+09	0.22	1.03E+10
1AIT3L6F	Transverse (WG)	4.24E+09	0.21	1.03E+10	5A1T3L6F	Transverse (WG)	4.37E+09	0.21	1.06E+10
1A4T3L2F	Transverse (WG)	4.12E+09	0.19	9.80E+09	5B3T2L2FR	Transverse (WG)	4.31E+09	0.20	1.04E+10
1A4T3L4F	Transverse (WG)	4.13E+09	0.18	9.78E+09	5B3T2L4F	Transverse (WG)	4.28E+09	0.20	1.03E+10
1A4T3L6F	Transverse (WG)	4.24E+09	0.19	1.01E+10	5B3T2L6F	Transverse (WG)	4.29E+09	0.20	1.03E+10
1A4T2L2F	Transverse (WG)	4.15E+09	0.18	9.84E+09	5B3T3L2F	Transverse (WG)	4.29E+09	0.20	1.03E+10
1A4T2L4F	Transverse (WG)	4.11E+09	0.18	9.72E+09	5B3T3L4F	Transverse (WG)	4.25E+09	0.20	1.02E+10
1A4T2L6F	Transverse (WG)	4.08E+09	0.18	9.64E+09	5B3T3L6F	Transverse (WG)	4.28E+09	0.20	1.03E+10
1B2T2L2F	Transverse (WG)	4.27E+09	0.20	1.03E+10					
1B2T2L4F	Transverse (WG)	4.29E+09	0.20	1.03E+10					
1B2T2L6F	Transverse (WG)	4.28E+09	0.20	1.03E+10					
1B2T3L2F	Transverse (WG)	4.35E+09	0.19	1.04E+10					
1B2T3L4F	Transverse (WG)	4.22E+09	0.21	1.02E+10					

Table A.17. Sonic velocity (TOF) derived elastic constants for graphite grade 2114 billet 116310 in the WG orientation sorted by in-billet location (continued)

Specimen number	Grain orientation	ELASTIC CONSTANTS			Specimen number	Grain orientation	ELASTIC CONSTANTS		
		Shear modulus, [Pa]	Poisson's ratio	Poisson's corrected elastic modulus, [Pa]			Shear modulus, [Pa]	Poisson's ratio	Poisson's corrected elastic modulus, [Pa]
		$G\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$			$G=\rho\upsilon_s^2$	$\mu=(1-[2(\upsilon_s/\upsilon_l)^2])/(2-[2(\upsilon_s/\upsilon_l)^2])$	$E=\rho\upsilon_l^2[(1+\mu)(1-2\mu)/(1-\mu)]$
1B2T3L6F	Transverse (WG)	4.19E+09	0.20	1.01E+10					
1B3T2L2F	Transverse (WG)	4.44E+09	0.20	1.07E+10					
1B3T2L4F	Transverse (WG)	4.44E+09	0.20	1.06E+10					
1B3T2L6F	Transverse (WG)	4.35E+09	0.20	1.04E+10					
1B3T3L2F	Transverse (WG)	4.33E+09	0.20	1.04E+10					
1B3T3L4F	Transverse (WG)	4.44E+09	0.20	1.06E+10					
1B3T3L6F	Transverse (WG)	4.36E+09	0.21	1.05E+10					

Table A.18. Four-point loading flexure strength for the flex strength specimens from billet 116310, tested here

Grain orientation	Flexure strength	Specimen number	Grain orientation	Flexure strength
	MPa			MPa
Parallel (AG)	39.32	1A1T2L2F	Transverse (WG)	43.79
Parallel (AG)	38.61	1A1T2L4F	Transverse (WG)	42.12
Parallel (AG)	38.72	1A1T2L6F	Transverse (WG)	40.54
Parallel (AG)	44.52	1AIT3L2F	Transverse (WG)	43.59
Parallel (AG)	38.43	1AIT3L4F	Transverse (WG)	43.26
Parallel (AG)	39.92	1AIT3L6F	Transverse (WG)	44.09
Parallel (AG)	38.38	1A4T3L2F	Transverse (WG)	43.01
Parallel (AG)	38.76	1A4T3L4F	Transverse (WG)	41.52
Parallel (AG)	39.05	1A4T3L6F	Transverse (WG)	41.12
Parallel (AG)	44.52	1A4T2L2F	Transverse (WG)	37.92
Parallel (AG)	44.56	1A4T2L4F	Transverse (WG)	42.21
Parallel (AG)	41.24	1A4T2L6F	Transverse (WG)	37.48
Parallel (AG)	41.83	1B2T2L2F	Transverse (WG)	40.18
Parallel (AG)	42.80	1B2T2L4F	Transverse (WG)	36.15
Parallel (AG)	38.21	1B2T2L6F	Transverse (WG)	42.53
Parallel (AG)	42.08	1B2T3L2F	Transverse (WG)	43.68
Parallel (AG)	37.19	1B2T3L4F	Transverse (WG)	40.21
Parallel (AG)	38.51	1B2T3L6F	Transverse (WG)	42.04
Parallel (AG)	39.89	1B3T2L2F	Transverse (WG)	45.14
Parallel (AG)	38.77	1B3T2L4F	Transverse (WG)	45.97
Parallel (AG)	43.18	1B3T2L6F	Transverse (WG)	45.39
Parallel (AG)	42.32	1B3T3L2F	Transverse (WG)	43.13
Parallel (AG)	39.24	1B3T3L4F	Transverse (WG)	42.87
Parallel (AG)	39.39	1B3T3L6F	Transverse (WG)	47.59
Parallel (AG)	44.89	5A1T2L2F	Transverse (WG)	47.11
Parallel (AG)	43.99	5A1T2L4F	Transverse (WG)	45.00
Parallel (AG)	42.22	5A1T2L6F	Transverse (WG)	43.95
Parallel (AG)	44.13	5A1T3L2FR	Transverse (WG)	45.46
Parallel (AG)	43.92	5A1T3L4F	Transverse (WG)	45.03
Parallel (AG)	44.99	5A1T3L6F	Transverse (WG)	43.16

Table A.18. Four-point loading flexure strength for the flex strength specimens from billet 116310, tested here (continued)

Grain orientation	Flexure strength	Specimen number	Grain orientation	Flexure strength
	MPa			MPa
Parallel (AG)	44.24	5B3T2L2FR	Transverse (WG)	47.37
Parallel (AG)	45.54	5B3T2L4F	Transverse (WG)	41.95
Parallel (AG)	42.64	5B3T2L6F	Transverse (WG)	46.77
Parallel (AG)	48.42	5B3T3L2F	Transverse (WG)	43.68
Parallel (AG)	49.45	5B3T3L4F	Transverse (WG)	46.07
Parallel (AG)	46.42	5B3T3L6F	Transverse (WG)	47.17