INL/MIS-23-70949-Revision-0

Baseline Characterization Database Verification Report - PCEA Billet 01S8-9

February 2023

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		Professional Engineer's Stamp
1. Effective Date	01/20/2023	NA See LWP-10010 for requirements
2. Does this ECAR involve a Safety SSC (see def. LWP-10200)?	No	
3. Safety SSC Determination Document ID	NA	
4. SSC ID	NA	
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6. Engineering Job (EJ) or Engineering Change (EC) No.	NA	
7. Building	IRC	
8. Site Area	REC	

9. Objective / Purpose

The purpose of this engineering calculations and analysis report (ECAR) is to present data collected in the Baseline Graphite Characterization Program, which is directly tasked with supporting the Idaho National Laboratory's (INL's) research and development efforts on the Advanced Reactor Technologies (ART) Program. This program populates a comprehensive database that reflects the baseline properties of nuclear-grade graphite with regard to individual grade, billet, and position within individual billets. The physical- and mechanical-property information being collected will be transferred to the Nuclear Data Management and Analysis System (NDMAS), and that database will help populate the handbook of property data available to member nations of the Generation-IV International Forum.

Transfer of these data from the applicable technical lead to the dissemination databases available to other end users requires a full review of the test procedures and data-collection efforts through an analysis of the multiple summary spreadsheets and values being collected. This report represents the analysis for PCEA Billet 01S8-9 and facilitates release of associated data to the NDMAS custodians.

10. If revision, please state the reason and list sections and/or page being affected.

NA

11. Conclusion / Recommendations

A review of data spreadsheets compiled from physical- and mechanical-property measurements on nuclear-grade graphite PCEA Billet 01S8-9 revealed no notable errors or omissions that preclude the transfer of these data to the NDMAS site for storage.

A full visual review of data files to determine whether obvious errors, such as missing information, was made regarding the data collected. Additionally, graphical representations were made of individual evaluations in order to provide a means to identify anomalies. The techniques employed are an adequate means to ensure the comprehensive data collected are reflective of the intended values of interest. A review of the data indicates that the files, as submitted, are fully representative of the measured properties of graphite billets being tested, as outlined in the applicable test procedures and program plans.

It is noted that PCEA Billet 01S8-9 was from the second PCEA purchased lot from GrafTech International Ltd. which was later found to have additional porosity which may have decreased the mechanical strength measured within some of the specimens during testing.

INL/MIS-22-65680

SIGNATURES

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1. Confirmation of completeness, mathematical accuracy, and correctness of data and appropriateness of assumptions.
2. Concurrence of method or approach. See definition, LWP-10106.
3. Concurrence of procedure compliance. Concurrence with method/approach and conclusion.
4. Concurrence with the document's assumptions and input information. See definition of Acceptance, LWP-10200.
5. Does the document contain CUI material please check either yes or no.

CONTENTS

APPENDIXES

1.0 PROJECT ROLES AND RESPONSIBILITIES

Project Role	Name	Organization	Pages Covered (if applicable)
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Nuclear Safety[f]	NA		
Document Owner[f]	William Windes	B612	All
Reviewer[f]	William Windes	B612	All

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d. Concurrence of procedure compliance. Concurrence with method/approach and conclusion.

e. Authorizes the commencement of work of the engineering deliverable.

f. Concurrence with the document’s assumptions and input information. See definition of Acceptance, LWP-10200.

NOTE: *Delete or mark “N/A” for project roles not engaged. Include ALL personnel and their roles listed above in the DCR system. The list of the roles above is not all inclusive. If needed, the list can be extended or reduced.*

2.0 SCOPE AND BRIEF DESCRIPTION

This ECAR provides the results of a validity evaluation of the physical and mechanical-property data collected on a billet of nuclear-grade graphite (i.e., PCEA Billet 01S8-9) in support of the ART Baseline Graphite Characterization Program.[1,2] It should be noted that PCEA Billet 01S8-9 was from the second PCEA purchased lot from GrafTech International Ltd., which formed additional porosity (informally identified as Wiggler Porosity) and caused long continuous pores to form during graphitization. These pores were large enough to directly affect some of the mechanical test specimens (resulting in a higher variability) that were machined from the billet for baseline testing.

Millions of raw data points have been collected during testing and quantification analyses for these billets. The summary scalar property values and supplementary traceability data are collected into comprehensive spreadsheets. Data sets are composed of single billets of graphite for any given grade, organized by mechanical test-specimen type, and further subdivided into individual spreadsheet tabs according to the specific test or evaluation being performed.

A direct analysis of properties was not conducted, and this report does not provide information on the validity or performance characteristics of the graphite itself. Rather, this report is intended as a verification of the completeness of actual data collected in accordance with PLN-3467, “Baseline Graphite Characterization Plan: Electromechanical Testing,”[3] and their representation of the measurement and test results with sole regard to the graphite billets under evaluation.

3.0 DESIGN OR TECHNICAL PARAMETER INPUT AND SOURCES

Mechanical- and physical-property testing is carried out in accordance with PLN-3348, “Graphite Mechanical Testing”[2]; PLN-3467, “Baseline Graphite Characterization Plan: Electromechanical Testing”[3]; and PLN-3267, “AGC-2 Characterization Plan.”[4]

4.0 RESULTS OF LITERATURE SEARCHES AND OTHER BACKGROUND DATA

N/A

5.0 ASSUMPTIONS

N/A

6.0 COMPUTER CODE VALIDATION

Data collection and storage are organized as reported in PLN-3467[3] and INL/EXT-10-19910, *Baseline Graphite Characterization: First Billet*.[5] The individual computers being used run Windows 7 operating systems and store data on Microsoft Office Excel 2007 spreadsheets.

Control of individual test equipment is carried out by proprietary Netzsch software (IRC C-20) or Instron’s Bluehill (Version 2) software (load frames in IRC B-11). Both software suites are commercially available packages. Updates, data transfers, and integrations are handled outside of INL’s network system on a dedicated local area network.

The comprehensive interface between data collection, evaluation, and storage computers is handled through the customized LabVIEW-based Graphite Mechanical Properties Data Acquisition Software (Version 4.0). The Baseline Graphite Characterization Program's version control and operability checks are documented and validated in a registered laboratory notebook, LAB 2143, "Baseline Graphite Characterization." Validation of commercial packages is handled via integrated system checks specific to each new element or upgrade, as appropriate.[6]

7.0 DISCUSSION/ANALYSIS

7.1 Introduction

The ART Project Graphite Research and Development Program generates the extensive quantitative data necessary for predicting behavior and operating performance of available nuclear graphite grades. To determine in-service behavior of graphite for the latest proposed designs, two main programs are underway. The Advanced Graphite Creep (AGC) Program provides a set of tests that are designed to evaluate the irradiated properties and behavior of nuclear-grade graphite over a large spectrum of conditions, based on the operating environment of the very-high-temperature reactor core.[1] A limited amount of data can be generated on irradiated material because of the availability of space within the Advanced Test Reactor and the geometric constraints placed on the AGC specimens that will be inserted into the reactor. To supplement the AGC data set, the Baseline Graphite Characterization Program provides additional data that will characterize inherent property variability in nuclear-grade graphite without the testing constraints of the AGC Program.[2] This variability in properties is a natural artifact of graphite due to the geologic raw materials that are used in its production. This variability is quantified, not only within a single billet of as-produced graphite, but also from billets within a single lot, billets from different lots of the same grade, and across different billets of numerous grades of currently available nuclear graphite.

This report covers the release of physical and mechanical-property data from a billet of PCEA graphite. Graphite Billet PCEA 01S8-9 is a block of extruded graphite with a medium grain structure. The baseline mechanical properties database for this billet, plots of which are included throughout this report, is composed solely of scalar results from each of the different evaluations (i.e., mechanical testing and physical properties) in summary form, and comprises tabbed spreadsheets occupied by more than 49,000 cells of individual characteristics or property values and associated tagging information.

It should be noted that PCEA Billet 01S8-9 was from the second PCEA purchased lot from GrafTech International Ltd. (2008 INL Purchase Order 00074513, under Specification SPC-996), Figure 1. This second purchased lot of PCEA billets was found to have formed additional porosity (informally identified as Wiggler Porosity) which caused 70–80 mm long continuous pores to form during graphitization, Figure 2. Mechanical test specimens machined with the large pore structures demonstrated lower strength measurement during testing, which induced larger variability within the overall statistical average of the mechanical-property sample populations (tensile, flexural, and compression strengths). It is speculated that this mechanism may be responsible for the large mechanical strength variability of the PCEA sample population. Additionally, the Wiggler Porosity had a spatial effect on the density. The billets were exhibited lower density in the middle and higher density on the outer perimeter.

As a result, the overall PCEA density and mechanical strength variability for billets with fabrication identifiers XPC01S8 and XPC02S8 are greater than what has been found for the third purchased lot, XPC01D3.

Figure 1. Received billets from GrafTech International for INL purchase in 2008. Billets purchased under Purchase Order 00074513, with Specification SPC-996.

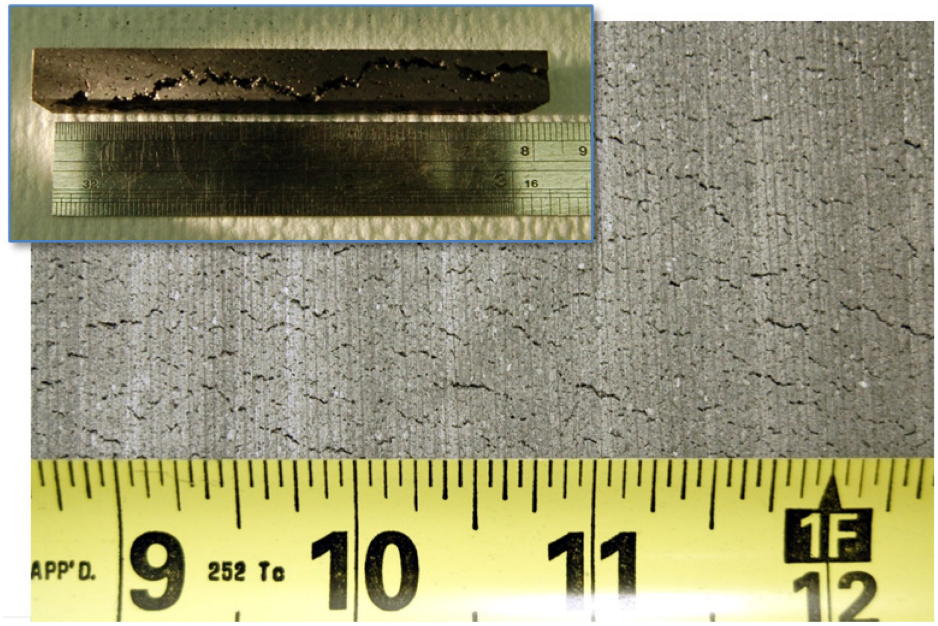

Figure 2. Microstructure image of PCEA graphite illustrating large continuous porosity formed during the PCEA graphitization step during fabrication.

This report is intended as a validation review of material property measurements for Graphite Billet PCEA 01S8-9. The report is not an analysis of property characteristics or trends beyond the evaluation necessary to determine whether the collected data are reflective of the properties of this particular graphite billet. The report is an acceptance of the test methods used and data calculations and conversions carried out and a review of values from the standpoint of determining whether they reflect anomalous behavior that must be further investigated.

Ultimately, this report provides justification for transfer of this data set into a storage and analysis system that is available for internal and external analysts to utilize in evaluating the relevant characteristics and performance of nuclear-grade graphite.

7.2 Database Analysis

The data sets being generated for the Baseline Graphite Characterization Program consist of properties collected on standard American Society of Testing and Materials (ASTM) international-based mechanical test specimens, as shown in Figure 3. Details of specimen tracking, traceability, process flow, and the techniques being employed to facilitate those activities are provided in INL/EXT-10-19910.[5] For ease of reviewing the applicable data in this report, an example of a sectioning diagram for PCEA graphite, along with the applicable specimen-identification codes, is provided in Figure 4. This figure is representative of a quarter of a single sub-wedge of graphite from this billet. Detailed drawings of PCEA graphite billet sectioning can be found in INL Drawings 759143 and 759293.[7,8]

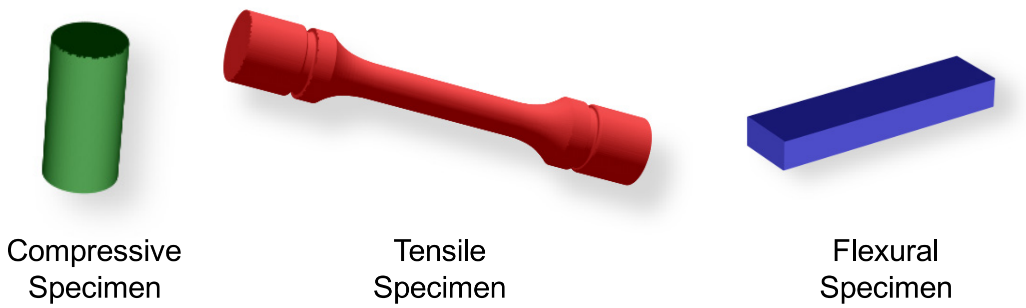

Figure 3. The three types of mechanical test specimens that will be machined from stock graphite and provide the basis for material property evaluations.

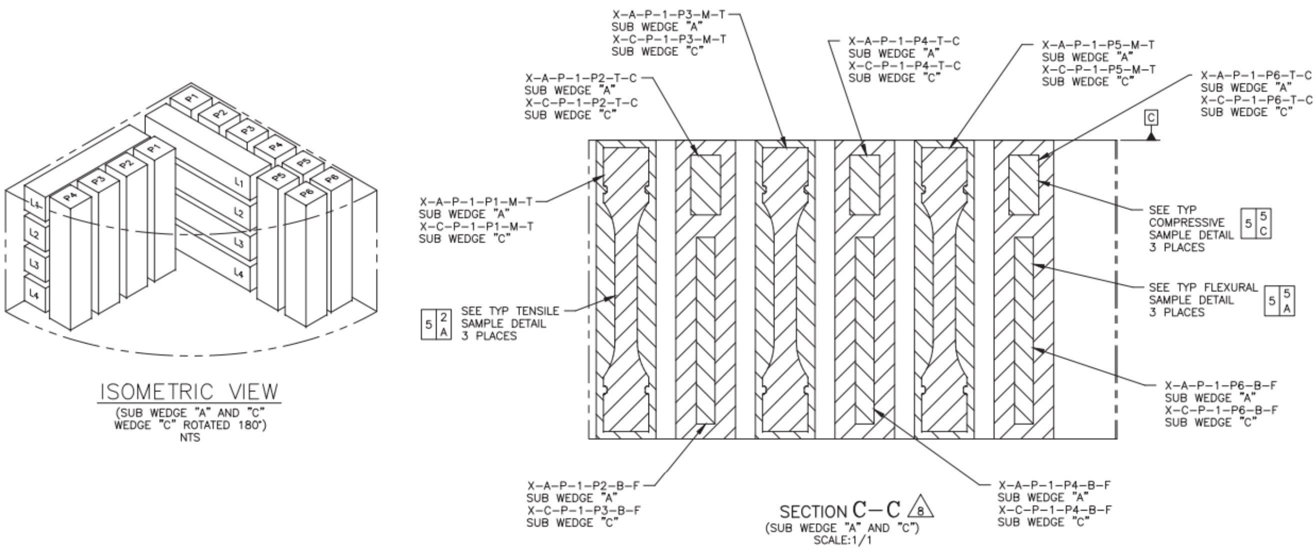

Figure 4. Individual specimen extraction and tracking identification from PCEA Billet 01S8-9.

Sections of this report covering each of the individual datasets for this billet, are divided by mechanical test-specimen type (e.g., compressive, flexural, or tensile), and are organized so they present data in graphical form. Graphic representations are not sorted in any way aside from the actual order in which they were tested, which was randomized for the express purpose of minimizing test anomalies based on actual test timeframes. Some expectation of variation in the property values exists, but individual data points that fall within a reasonable property value range are considered acceptable. Comparisons of extreme values with other associated properties (e.g., a comparison of maximum tensile load values with measured strain to determine whether they are related by the expected elastic modulus) are carried out where applicable. Each of these comparisons and analyses may not be explicitly included in this report. However, the process-control charts with standard-deviation values and/or property-trend charts for the various characteristics being measured are included both in this section as well as the appendices (±1, 2, and 3 standard deviations are represented by the yellow, orange, and red dotted lines, and the mean is represented by the green line).

A goal of the Baseline Graphite Characterization Program is to identify and quantify interbillet variation. However, the focus of this analysis is to compare values from complete data sets to quickly identify outlying points. One example would be a zero value for a specific property—quickly identifiable on a test-result trend graph—providing an indication that the specific spreadsheet cell is improperly empty. Another example would be a large disparity between a limited number of points on that same test-result trend graph that results from missing values in other cells (i.e., dimensional measurements from which final properties are calculated). This verification will couple those observations with a comprehensive data scan of individual points to determine whether the data set can be considered complete and the scalar summary points provided to the NDMAS are appropriately representative of the billet under evaluation.

7.3 Compression-Specimen Database (PCEA 01S8-9)

7.3.1 Compression Testing

Compression testing was performed per ASTM C695-15[9] and PLN-3467.[3] Figure 5 shows the maximum applied load for each of the 181 compression specimens from Billet 01S8-9. As was mentioned previously, some variation in graphite properties is expected, and this variation is reflected in the difference in test-frame loading. The compressive stress values (Figure 6) correlate directly with recorded load values (Figure 5), confirming the stress calculations were performed correctly. An additional check of critical-property values is the measured deflection (Figure 7) of the loading surface, or upper platen, as measured by a calibrated deflectometer. Within geometric variations, the deflection should reflect the calculated compressive strain, as shown in Figure 8. Other plots of supporting data from the compressive specimens are shown in Appendix A.

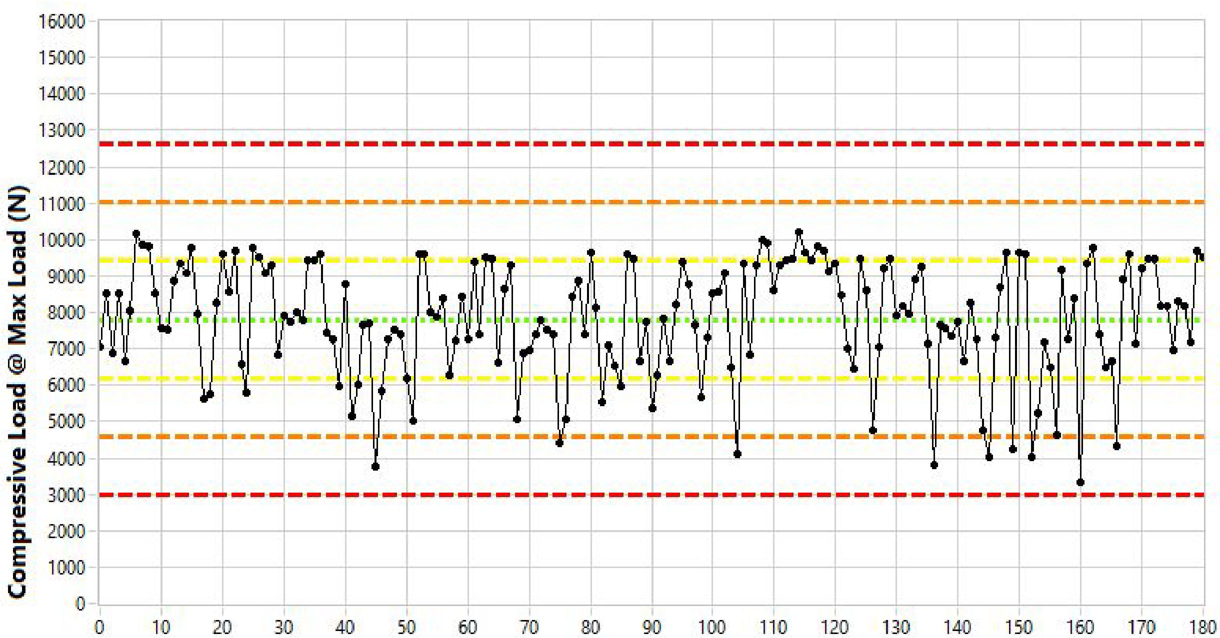

Figure 5. Compressive load at max load (N), mean = 7805.2, standard deviation = 1601.4.

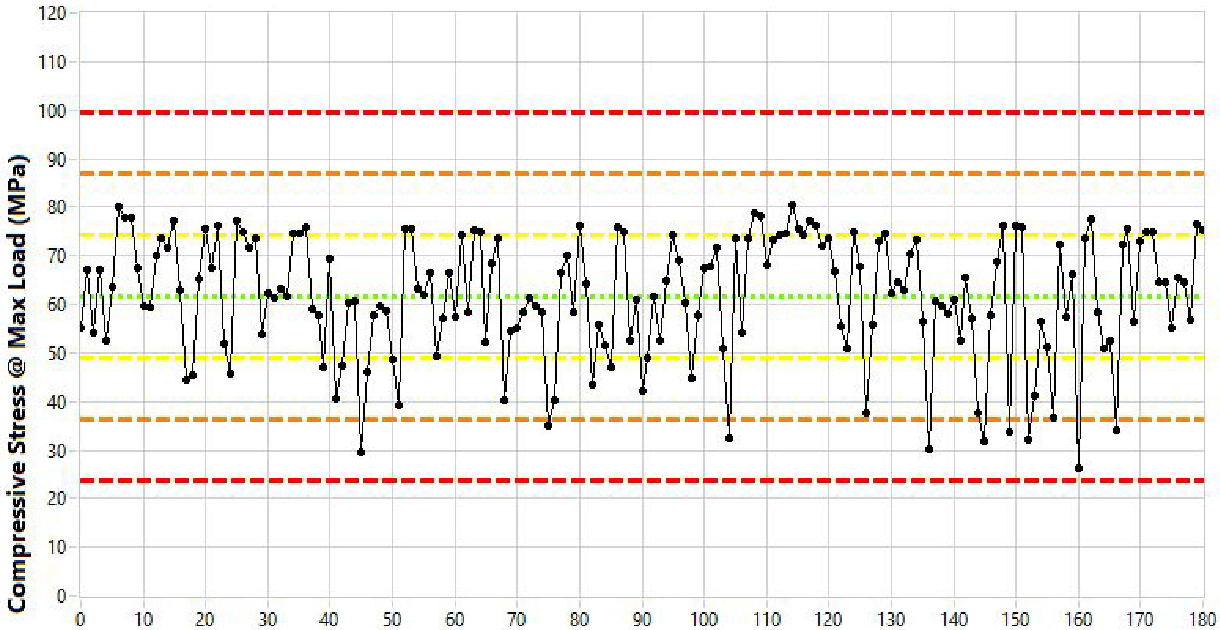

Figure 6. Compressive stress at max load (MPa), mean = 61.6, standard deviation = 12.6.

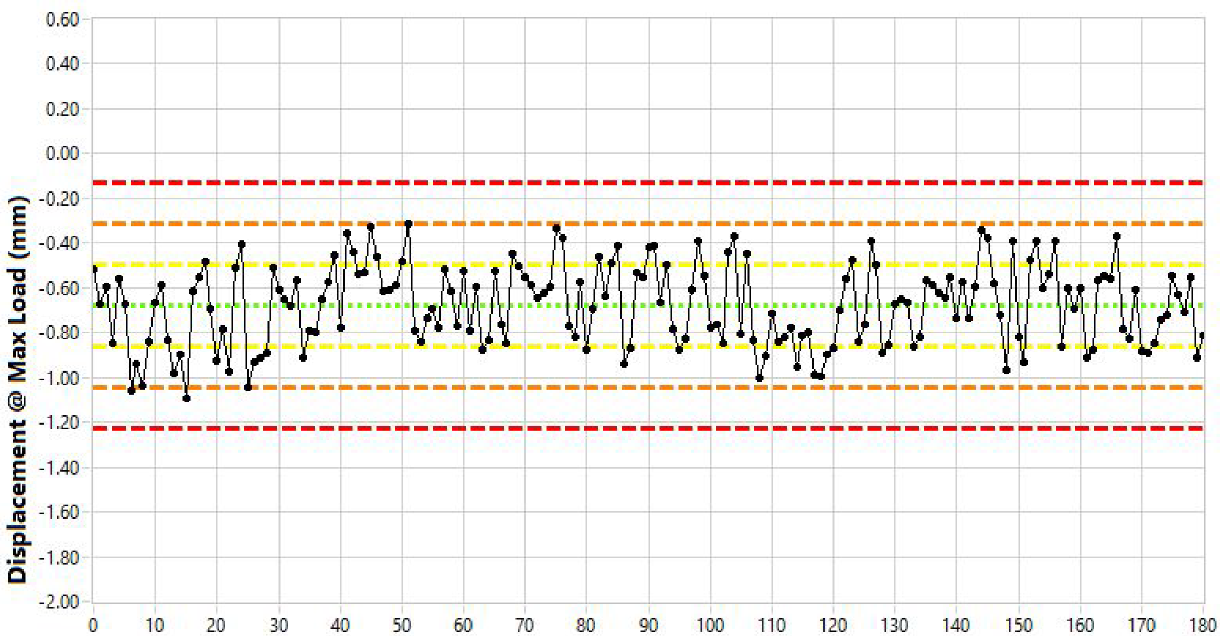

Figure 7. Displacement at max load (mm), mean = -0.680, standard deviation = 0.183.

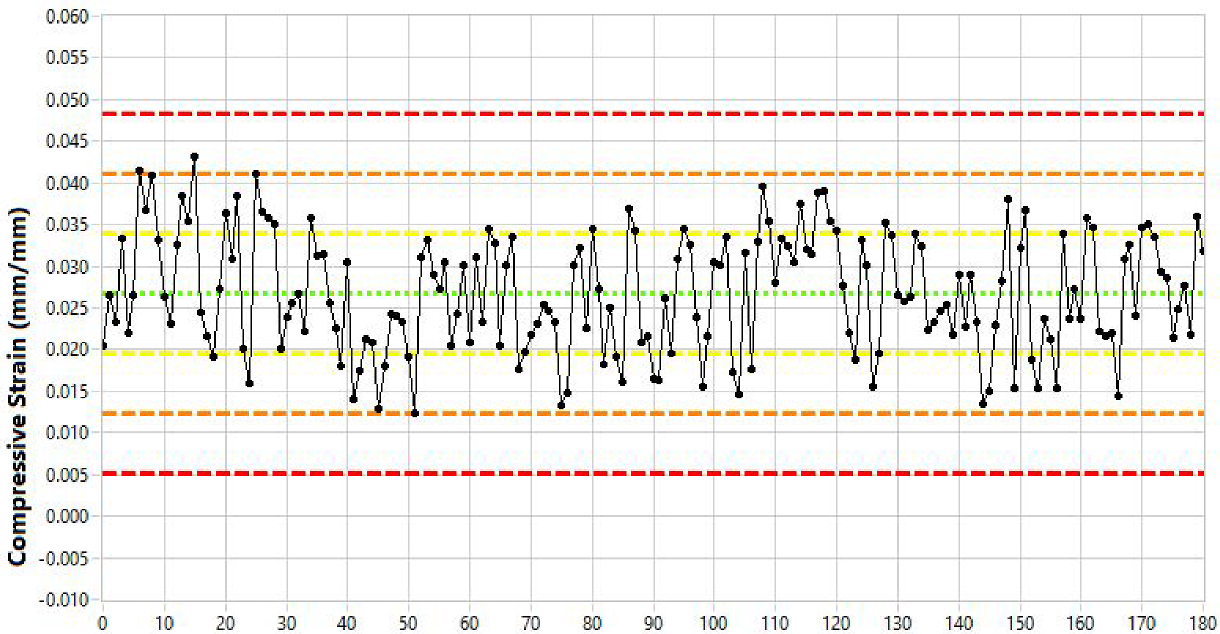

Figure 8. Compressive strain (mm/mm), mean = 0.0268, standard deviation = 0.0072.

7.3.2 Fracture Surface Categorization

Fracture surfaces from compressive specimens offer an additional opportunity to collect scalar data that can be sorted with respect to graphite type and position. To allow for consistency in what is essentially a qualitative attribute, a description of each of the fracture types is provided to the user of the Graphite Mechanical Properties Data Acquisition Software. Figure 9 is a screen shot of this categorization, along with the distribution of the recorded fracture categories for each of the 181 compressive specimens from PCEA Billet 01S8-9 (with no anomalous values indicative of an unallowable characterization).

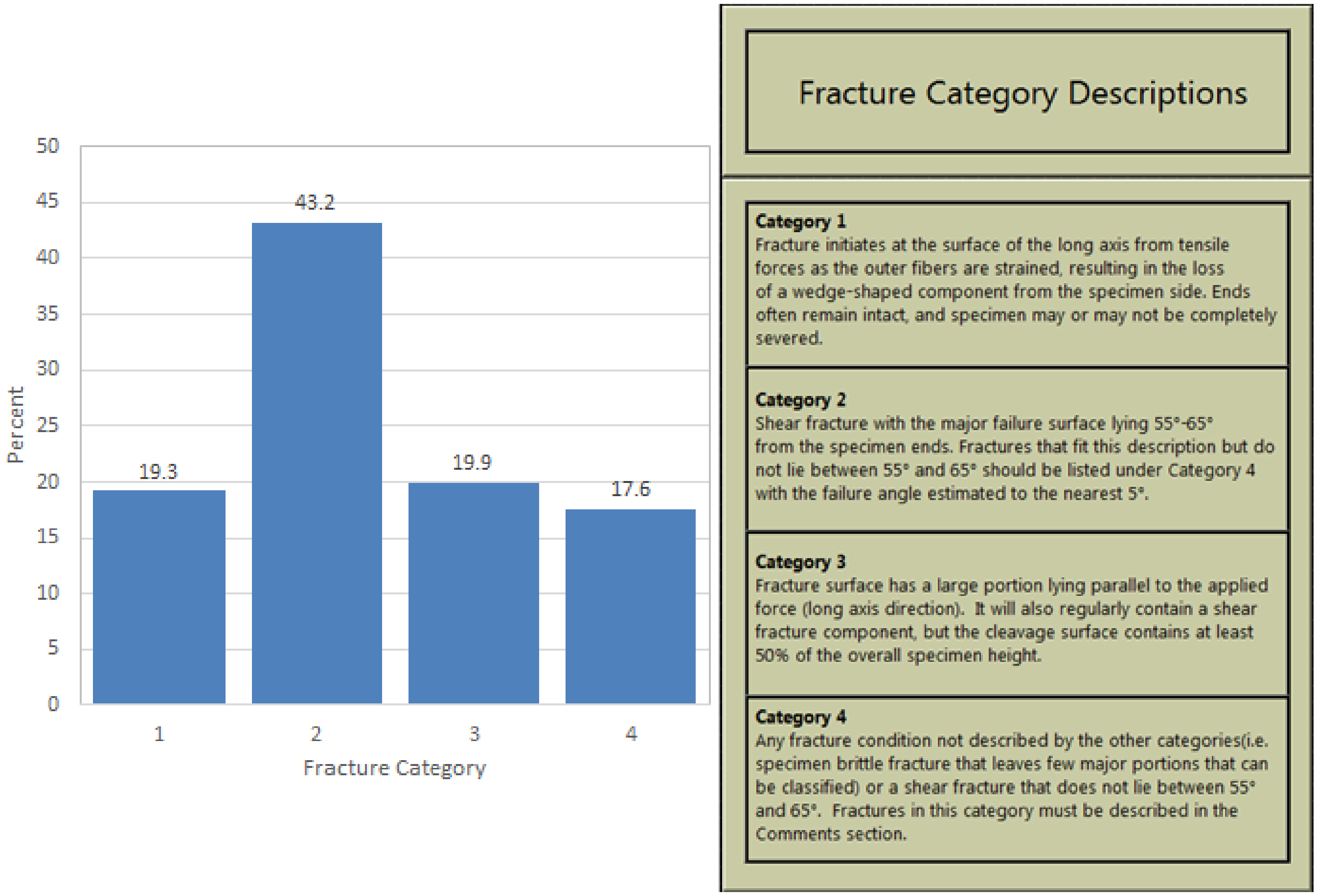

Figure 9. Fracture categorization results and description.

7.3.3 Electrical Resistivity, Modulus, and Coefficient of Thermal Expansion

Resistivity measurements were performed on 20 specimens before they were broken in compression. These values can be seen in Figure 10. All measurements fell within their expected range.

Young's and shear modulus by sonic velocity and Young's modulus by sonic resonance tests were performed on 63 compression specimens before they were broken. None of these data appear to vary significantly from known modulus values for PCEA graphite. These data are plotted in Figure 11 through Figure 13.

Figure 14 shows the coefficient of thermal expansion (CTE) from 20 compression specimens before they were broken. These data show a tight grouping over the 10 measurement temperatures. All of the above tests were carried out via the appropriate ASTM standards.[10,11,12,13,14]

Figure 10. Resistivity (μOhm-m), mean = 8.59, standard deviation = 0.39.

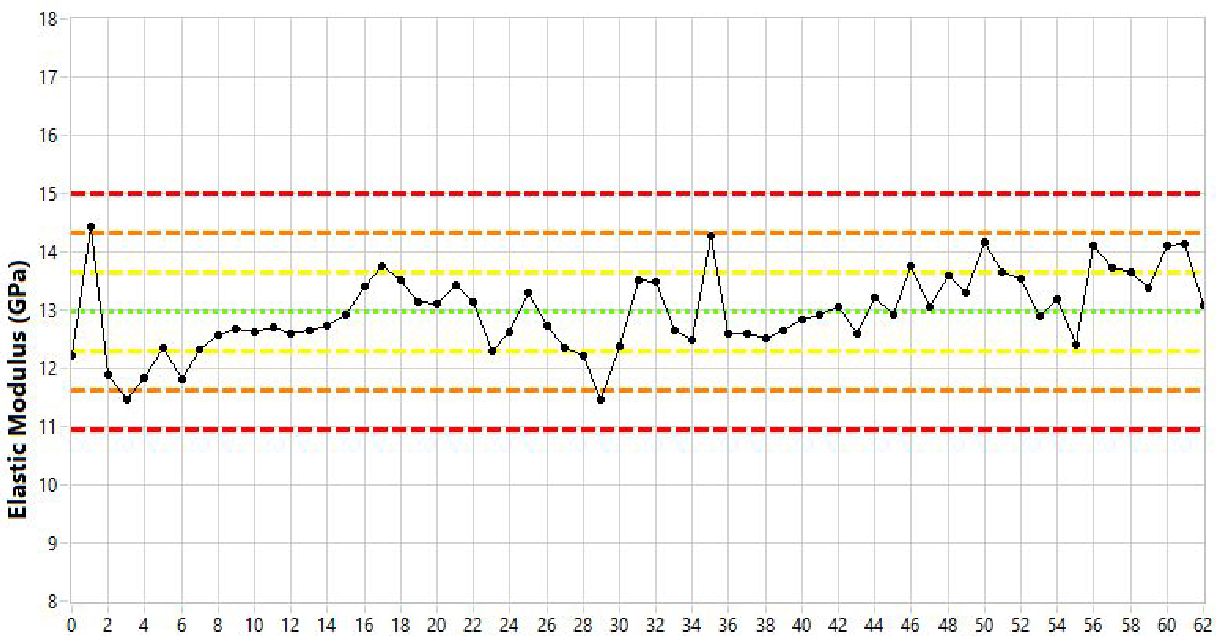

Figure 11. Elastic modulus by sonic velocity method (GPa), mean = 12.96, standard deviation = 0.68.

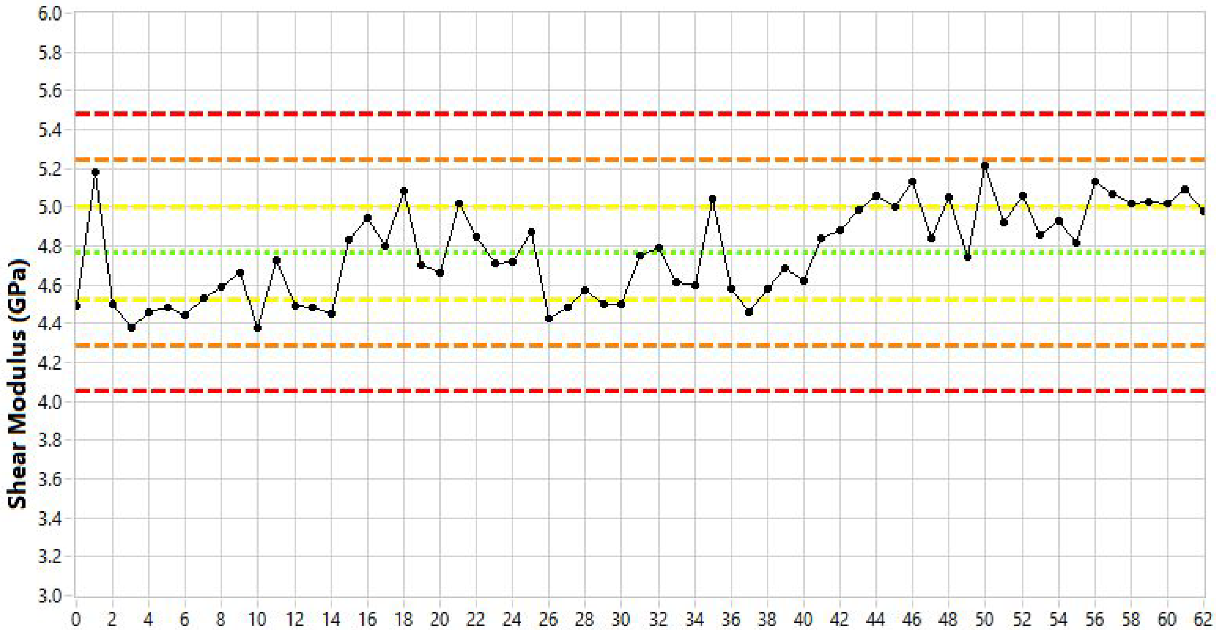

Figure 12. Shear modulus by sonic velocity method (GPa), mean = 4.77, standard deviation = 0.24.

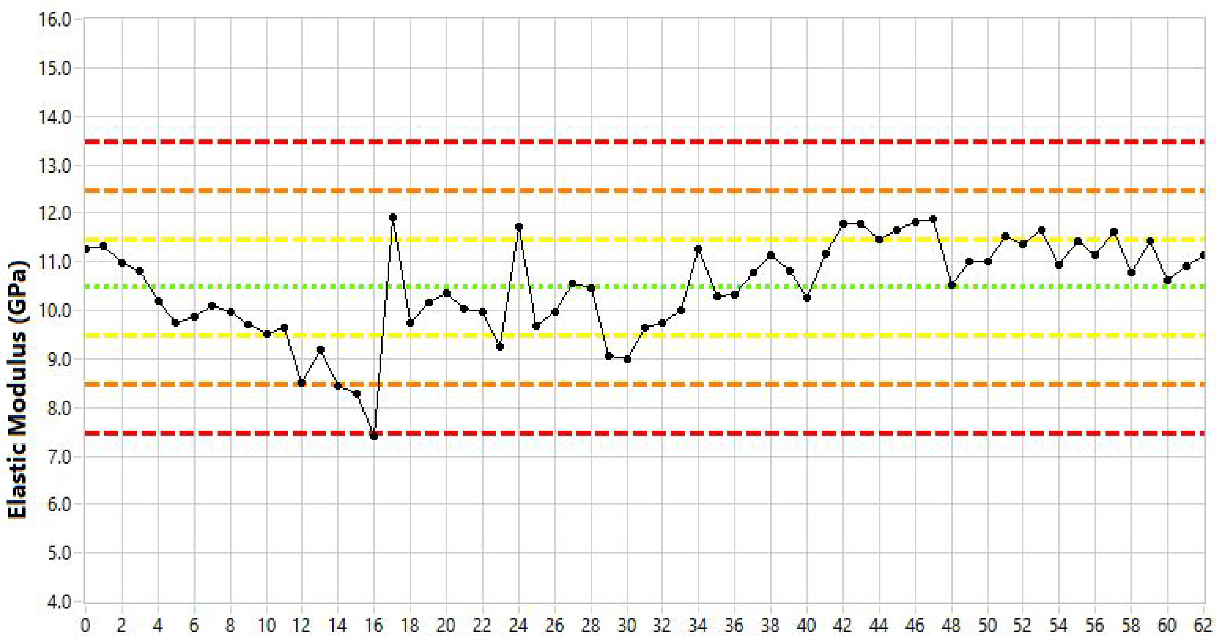

Figure 13. Elastic modulus by sonic resonance method (GPa), mean = 10.47, standard deviation -1.0.

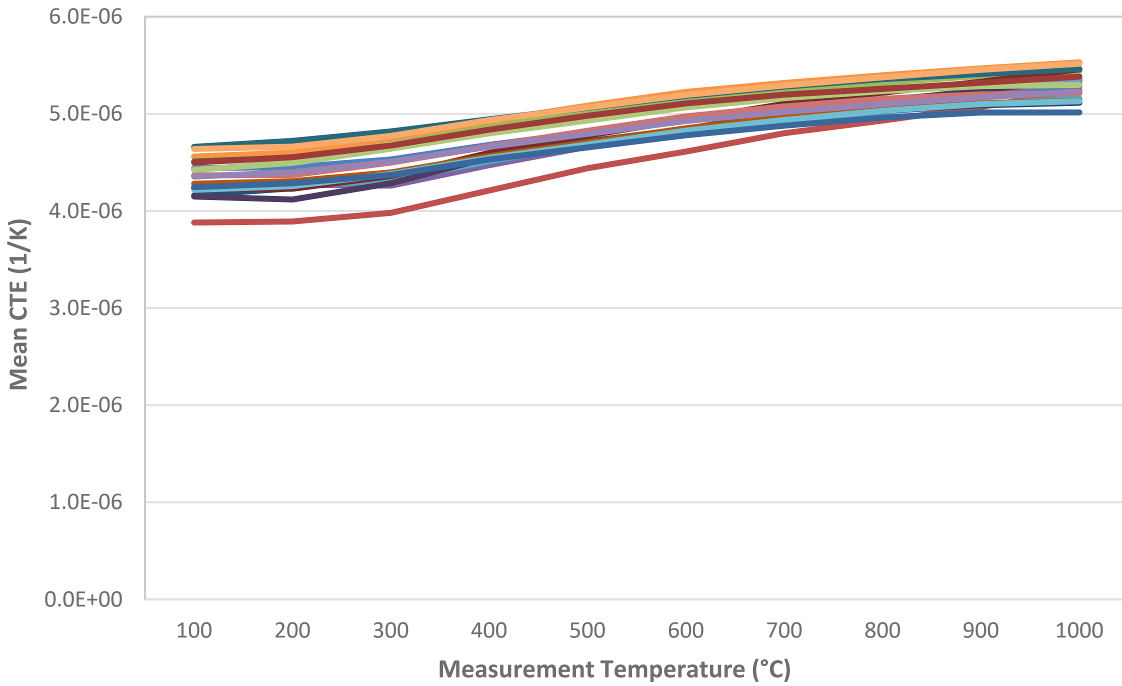

Figure 14. Mean CTE (1/K).

7.3.4 Density Values

The relatively simple geometric shape of the compressive specimens provides an opportunity to collect density data (per ASTM C559-90[15]) for a large portion of the specimens extracted from each billet. While not true performance properties, density measurements are relatively straightforward to collect and are often reflective of bulk mechanical properties. The density values recorded for the compression specimens (Figure 15) show one anomalous value. This value was deemed to be acceptable after reviewing the support data for their density values (mass and dimensions). Material variation and the porous nature of PCEA is expected to be the cause of the outlier.

Figure 15. Density (g/cm³), mean = 1.7882, standard deviation = 0.0305.

7.4 Flexural Specimen Database (PCEA 01S8-9)

7.4.1 Flexural Testing

Flexural testing was performed per ASTM C651-91,[16] with clarifications to ambiguities in the standard identified in PLN-3467.[3] As with the presentation of compression-specimen results, test validation lies not only in the documented adherence to applicable test plans and standards, but also in the noted correlations between recorded test properties and analyses for extreme or anomalous values. Additional verification of test conditions can be accomplished through an analysis of the physical characteristics of the specimens. Figure 16, Figure 17, and Figure 18 show the measured width, thickness, and length for all flexural specimens tested. Four of the width measurements and five of the length measurements fell outside of plus three standard deviations from the mean. However, the individual measurements all met ASTM C651-91 specifications and the specifications from Drawing 759293, so these data were kept.

Figure 19 and Figure 20 show the relationship between flexural load and recorded flexural stress for the 161 specimens tested in flexure from PCEA Billet 01S8-9. Further comparisons and verification can be made with measured deflection (Figure 21), which will reflect an additional correlation with stress values through material elastic constants. Figures 19, 20, and, 21 each show outliers (3, 3, and 2, respectively). These outliers are the result of specimens with voids present in the specimen structure. This led to extremely low strength values. These data will be kept in the database since they are indicative to the billet and the inherent strength of the PCEA graphite grade. Other plots of supporting data from the flexural specimens are shown in Appendix B.

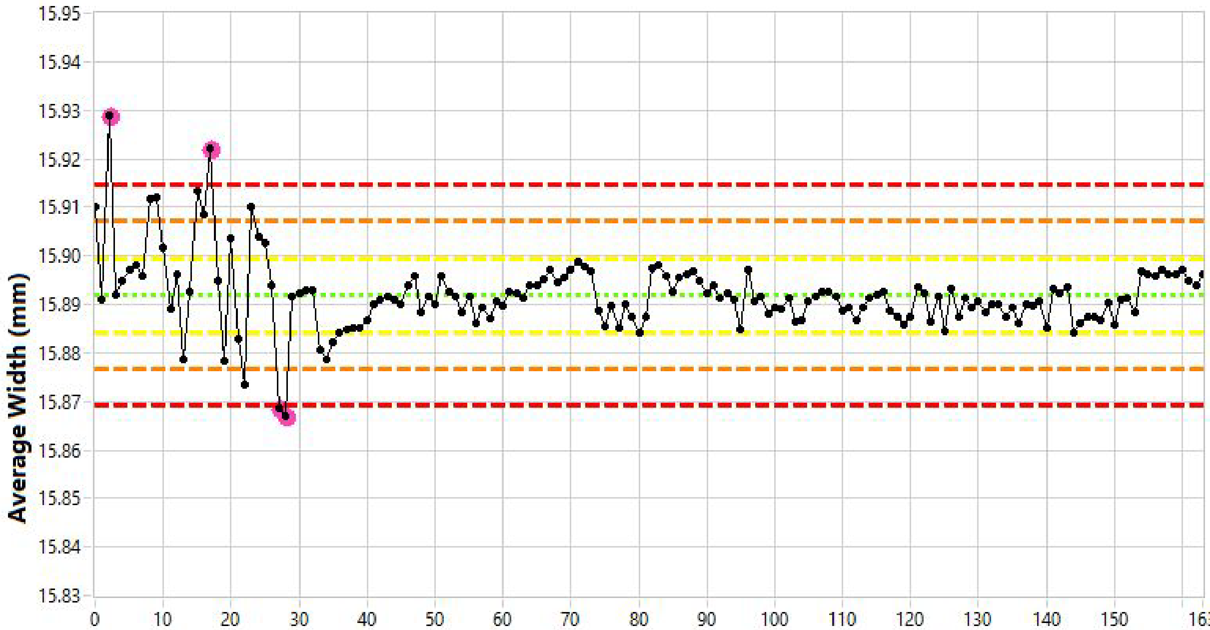

Figure 16. Average width (mm), mean = 15.8919, standard deviation = 0.0076.

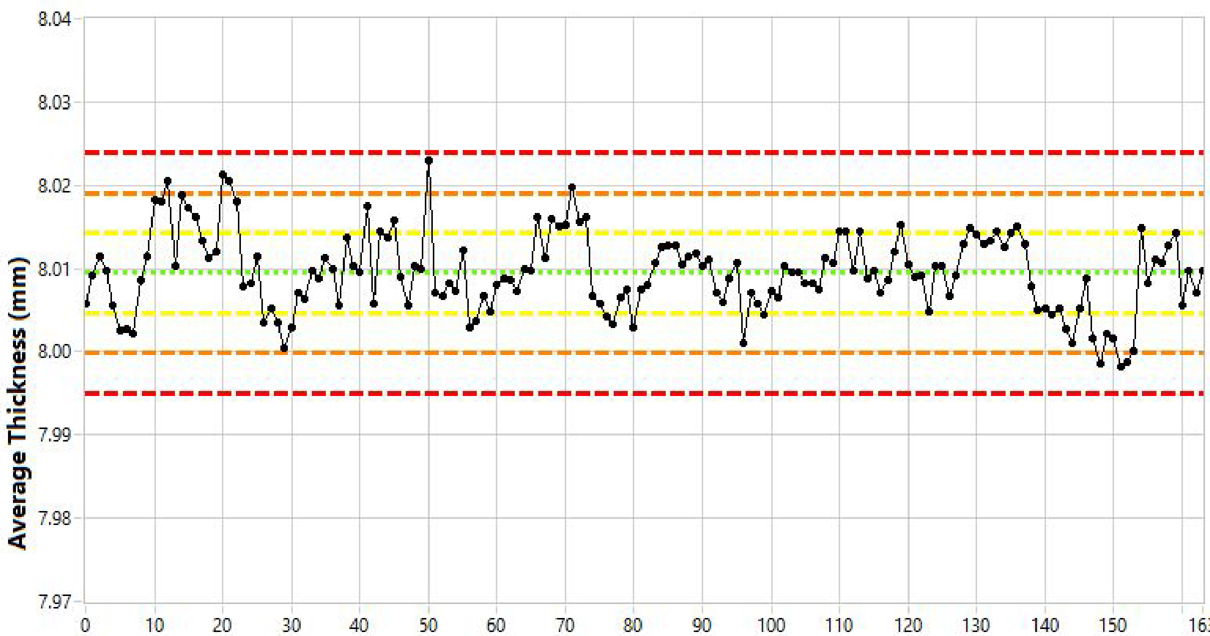

Figure 17. Average thickness (mm), mean = 8.0095, standard deviation = 0.0048.

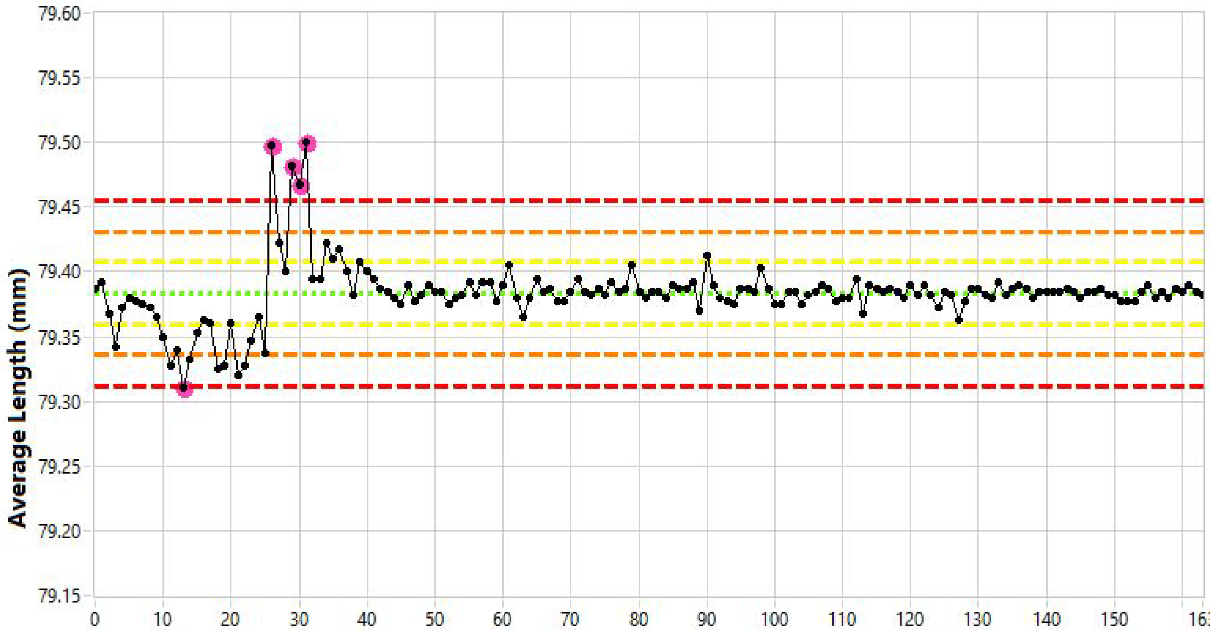

Figure 18. Average length (mm), mean = 79.3834, standard deviation = 0.0239.

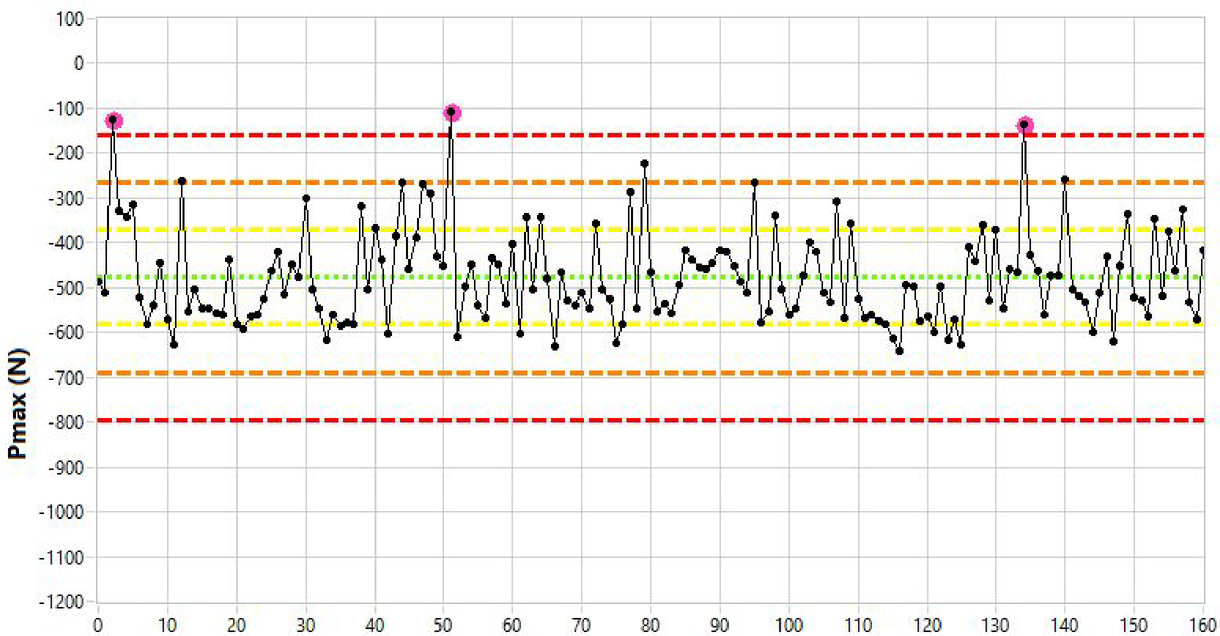

Figure 19. Max load (N), mean = -477.2, standard deviation = 105.9.

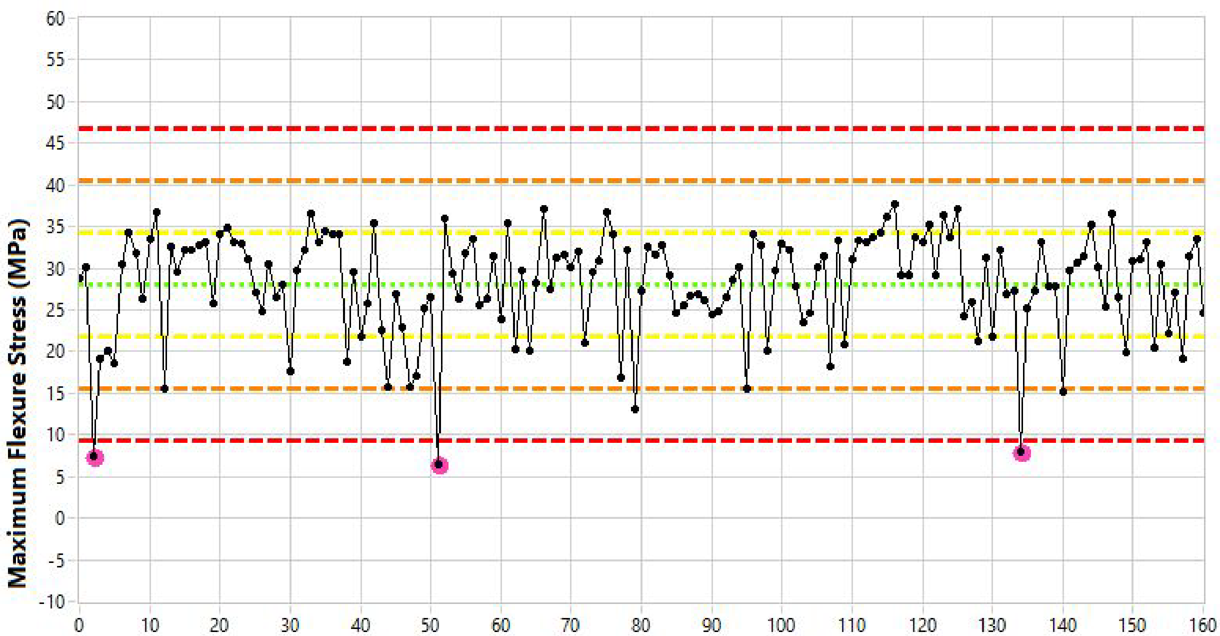

Figure 20. Maximum flexure stress (MPa), mean = 28.1, standard deviation = 6.2.

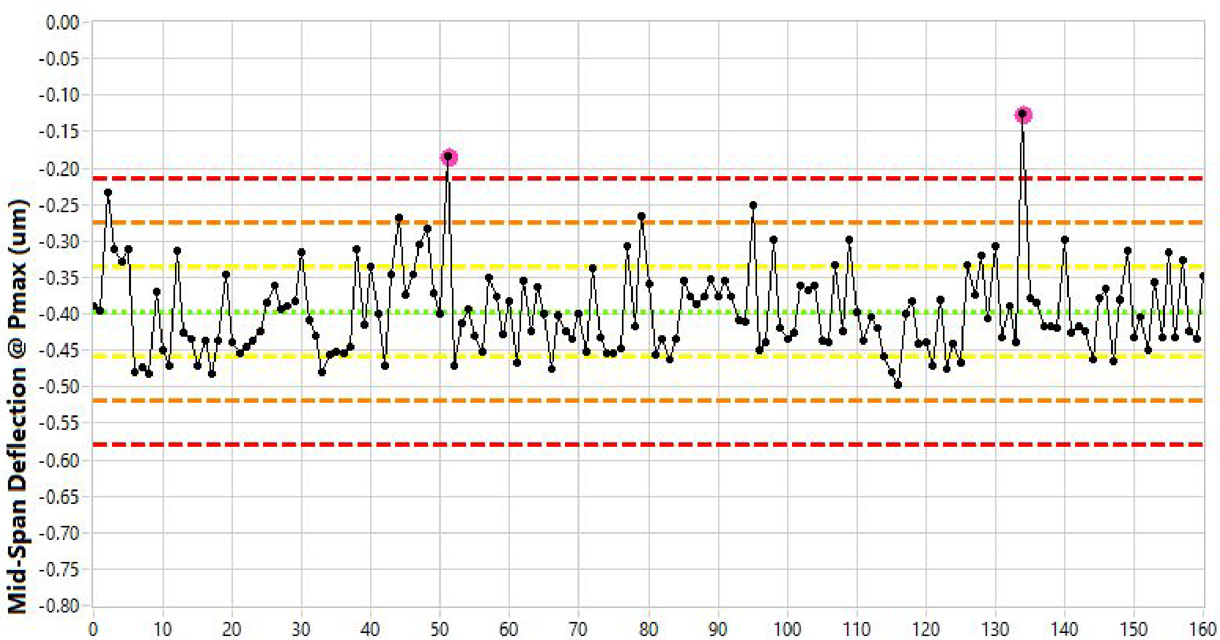

Figure 21. Mid-span deflection at max load (um), mean = -0.3969, standard deviation = 0.0611.

7.4.2 Density Values

Similar to the compression specimens, the flexural specimens' geometry facilitated an opportunity to measure density. Figure 22 shows density from the flexural specimens. All flexural specimens' data and associated deviations compare well with the compression specimens' density data.

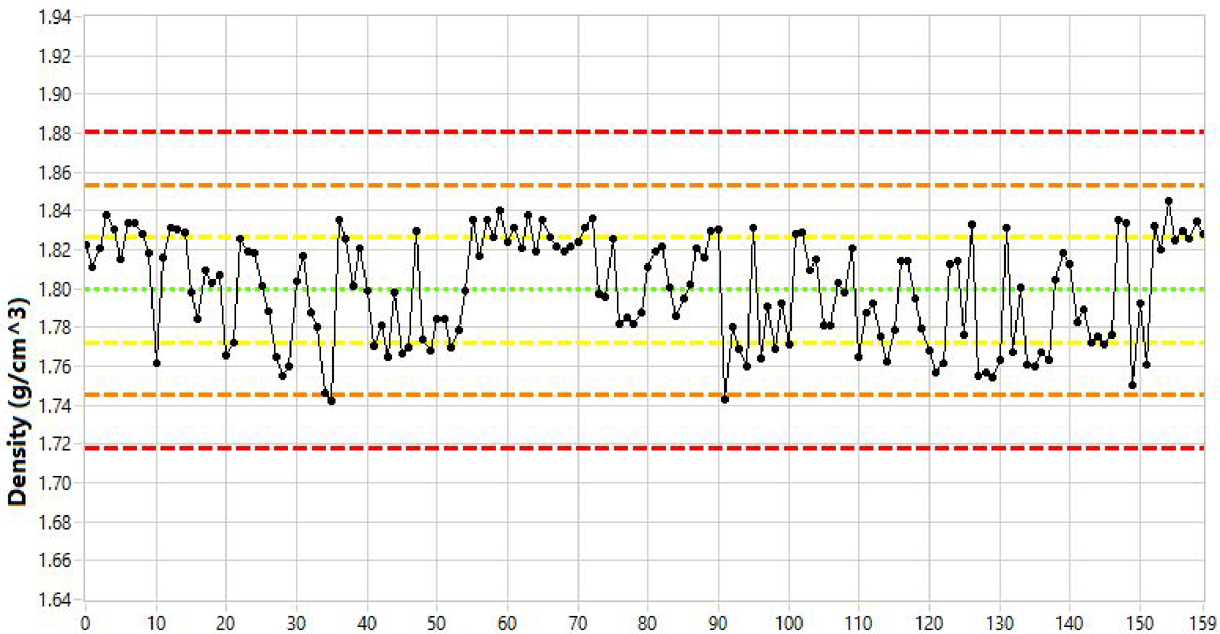

Figure 22. Density (g/cm^3), mean = 1.7994, standard deviation = 0.0271.

7.4.3 Fundamental Frequency

The precise parallelepiped geometry of flexural specimens renders them particularly valuable for accurate measurements of fundamental frequency to collect elastic constants for both dynamic Young's modulus and shear modulus (ASTM C747-93[11]). Values for fundamental-frequency-based moduli, both in flexural and torsional modes (shown in Figure 23 and Figure 24), are calculated from the equations provided in ASTM C1259-08.[12] Two of the flexural moduli values fell outside ±3 standard deviations from their respective means. Their frequency values were examined and found to be consistent, thus these data were kept and will be added to the database.

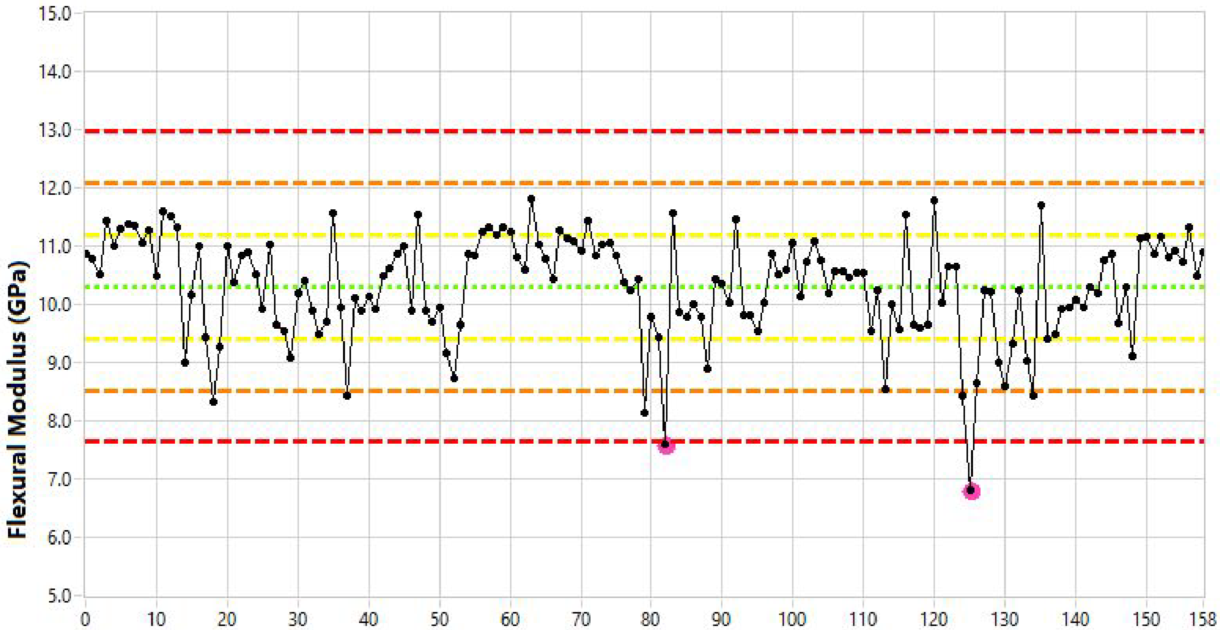

Figure 23. Flexural vibration mode modulus (GPa), mean = 10.30, standard deviation = 0.89.

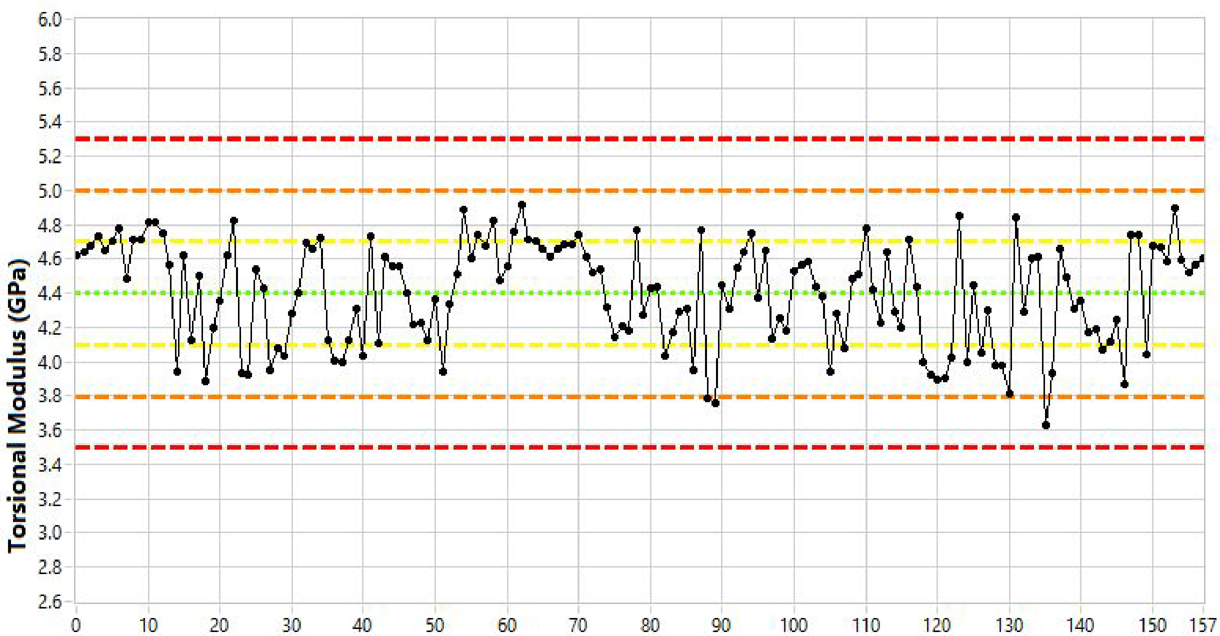

Figure 24. Torsional vibration mode modulus (GPa), mean = 4.40, standard deviation = 0.30.

7.5 Tensile Specimen Database (PCEA 01S8-9)

7.5.1 Tensile Testing

Tensile testing was performed per ASTM C749-08.[17] Data verification follows the principles discussed in previous sections. As with other specimen types, data verification lies not only in documented adherence to applicable test plans and standards, but in noted correlations between recorded test properties and analyses for outlying values. Additional verification of test conditions can be carried out through an analysis of ancillary physical characteristics.

A total of 152 specimens were tested in tension. Figure 25 shows the gauge diameters of the tensile specimens. (Note, there are 153-gauge diameter measurements. One of those specimens was not used in a tensile test.) Two of the minimum gauge diameter measurements from these specimens fell outside ±3 standard deviations of the mean. However, the six individual measurements that were taken to calculate the mean of each of the three specimens were consistent, so these data were kept.

Figure 26 and Figure 27 show the relationship between tensile load and recorded tensile strength for all the specimens tested in uniaxial tension from the PCEA Billet 01S8-9. Figure 28 shows the recorded tensile stress for the tested specimens. Further comparisons and verification can be made with extensometer-based measured strain (shown in Figure 29), which will reflect an additional correlation with stress values through material elastic constants. Comparing the extreme values again shows this relationship to be valid. Other plots of supporting data from the flexural specimens are shown in Appendix C.

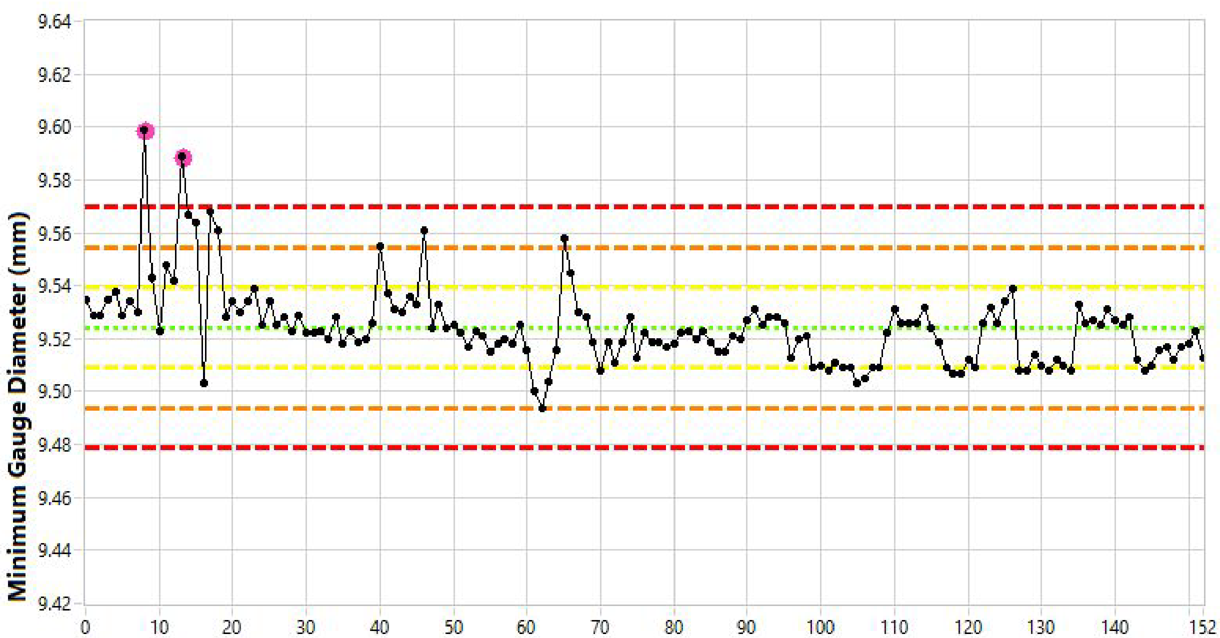

Figure 25. Minimum gauge diameter (mm), mean = 9.5243, standard deviation = 0.0151.

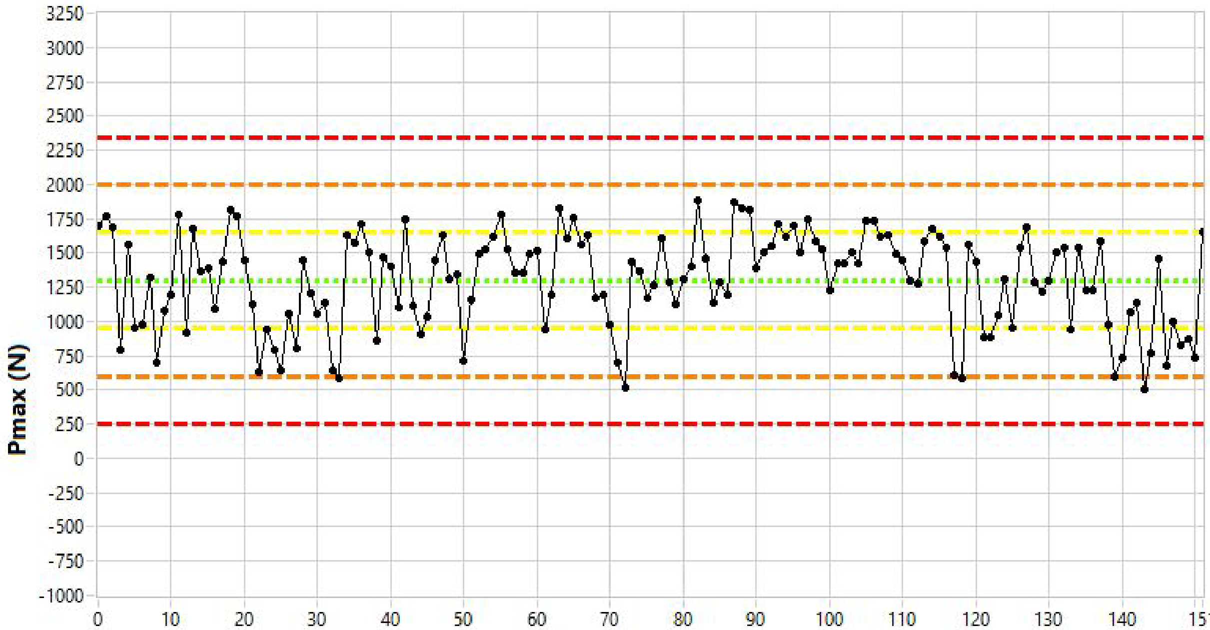

Figure 26. Max load (N), mean = 1300.2, standard deviation = 349.3.

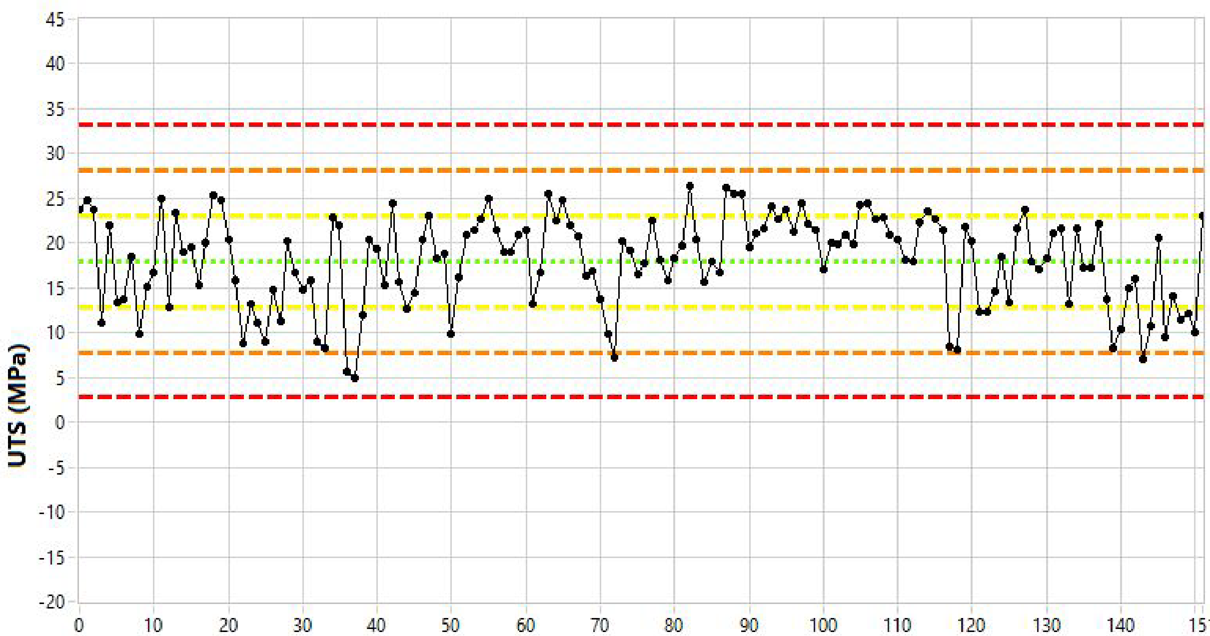

Figure 27. Uniaxial tensile strength (MPa), mean = 18.0, standard deviation = 5.1.

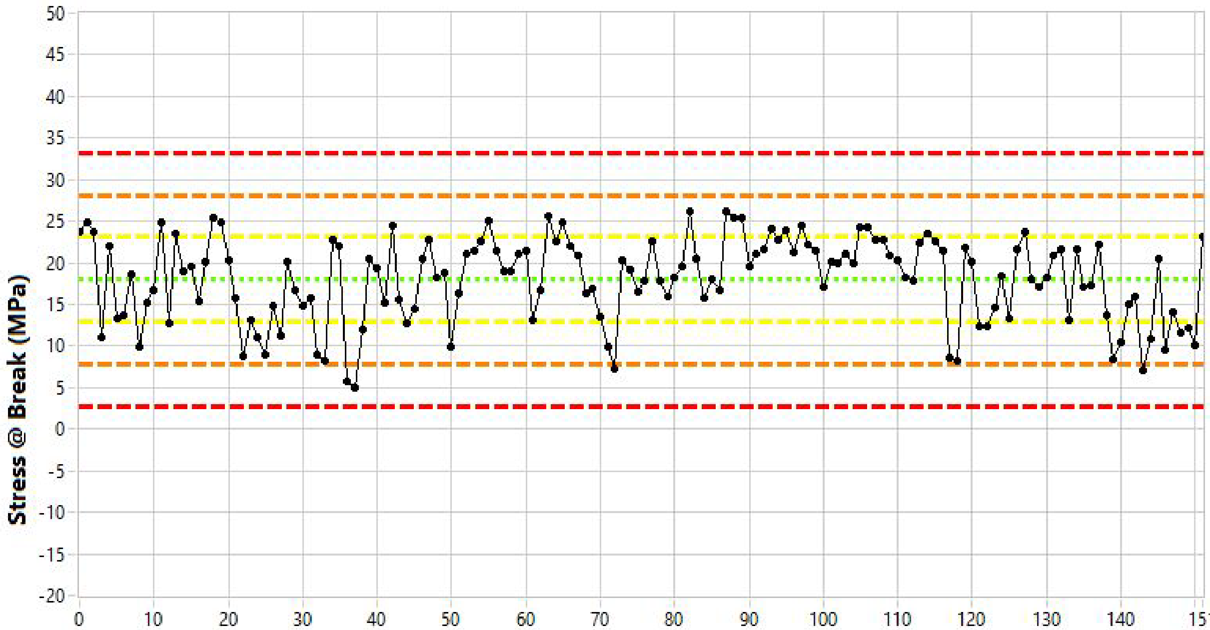

Figure 28. Stress at break (MPa), mean = 18.0, standard deviation = 5.1.

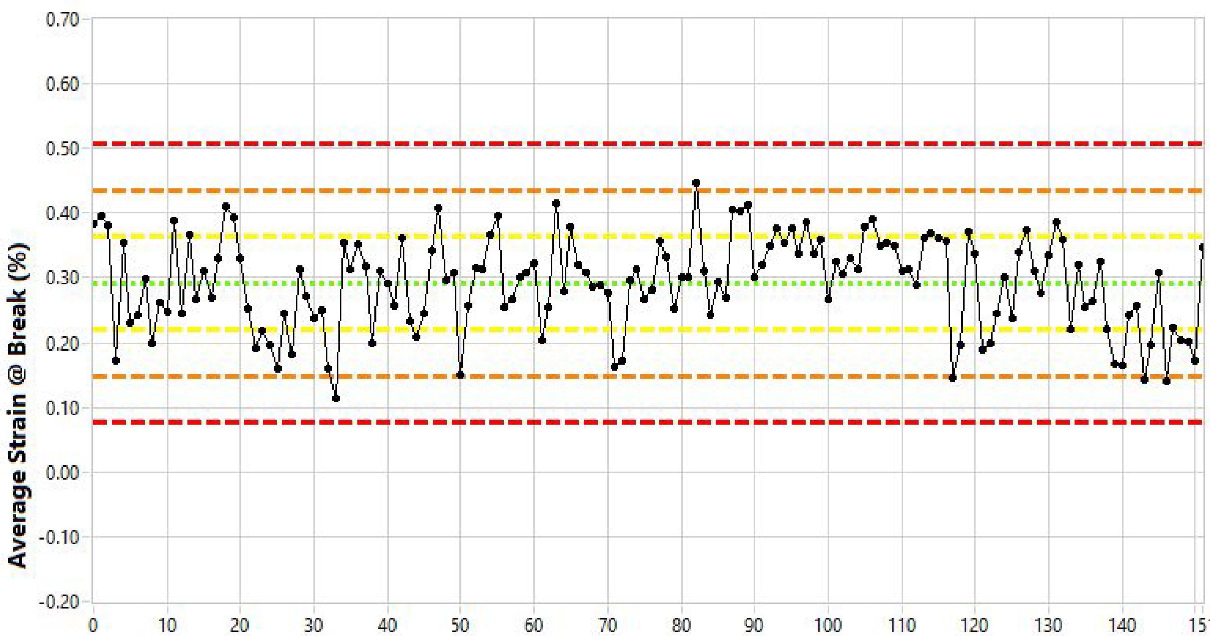

Figure 29. Average strain at break (%), mean = 0.2919, standard deviation = 0.0719.

8.0 RE-MACHINED SPECIMEN PROPERTIES

Two of the key components to direct comparisons between baseline and AGC data are (1) the analyses of specimens with similar geometries and (2) employment of similar test techniques for comprehensive validation. The geometry of the tensile specimens provides the opportunity to "re-machine" the unstressed sections of the specimen ends (shown in Figure 30) to the same dimensions as AGC piggyback specimens. A random cross-section of tensile specimens was re-machined to repeat tests on AGC-sized specimens (i.e., diffusivity and split-disc testing). Using actual test specimens for re-machining enables continued employment of the specimen identification and tracking code system, because specimens are machined from tracked locations and can reuse the identification code.

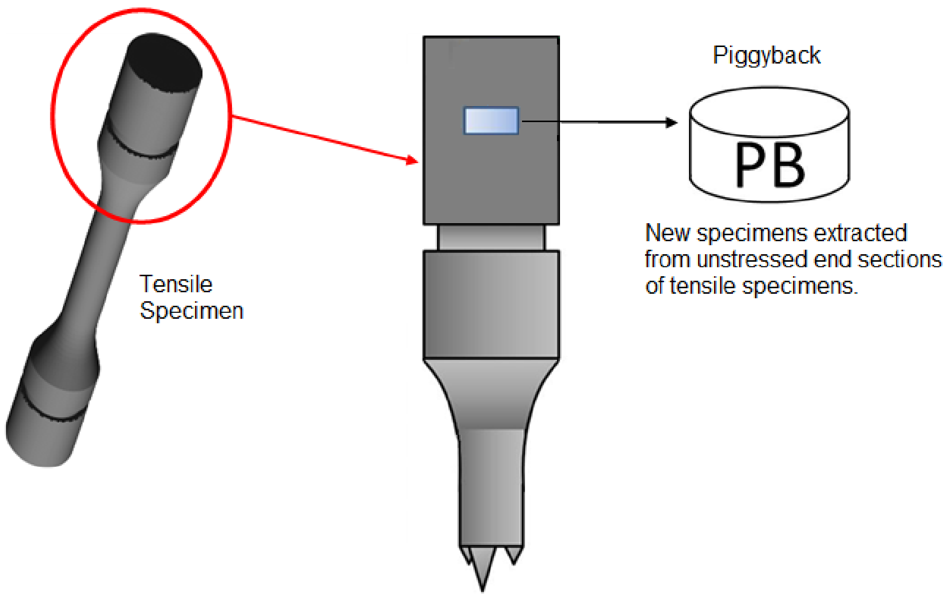

Figure 30. Unstressed specimen remnants from tensile specimens are re-machined into AGC-sized piggyback specimens.

9.0 RE-MACHINED SPLIT-DISC TESTING

Disc splitting tensile strength testing was performed in accordance with PLN-3348,[2] Revision 4 Section 6.1.1.5. This allows for a direct comparison of tensile data to data that were acquired through strict application of ASTM C749-08. Figure 31 and Figure 32 show strength and load data from the split-disc testing. The mean strength calculated from the split-disc testing was roughly 10% lower compared to the traditional tensile testing (Figure 27) but the standard deviation was about 20% lower. One of the 30 split-disc specimens had an extremely low-tensile strength. This is probably due to the porous nature of this PCEA billet.

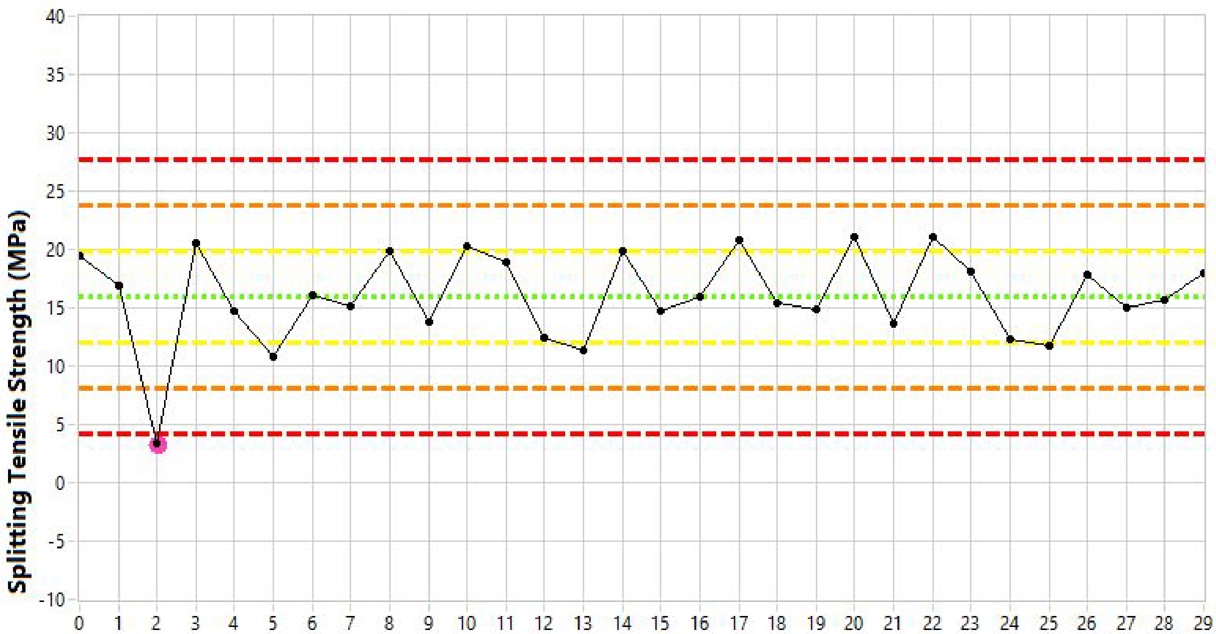

Figure 31. Disc splitting tensile strength (MPa), mean = 15.9849, standard deviation = 3.9175.

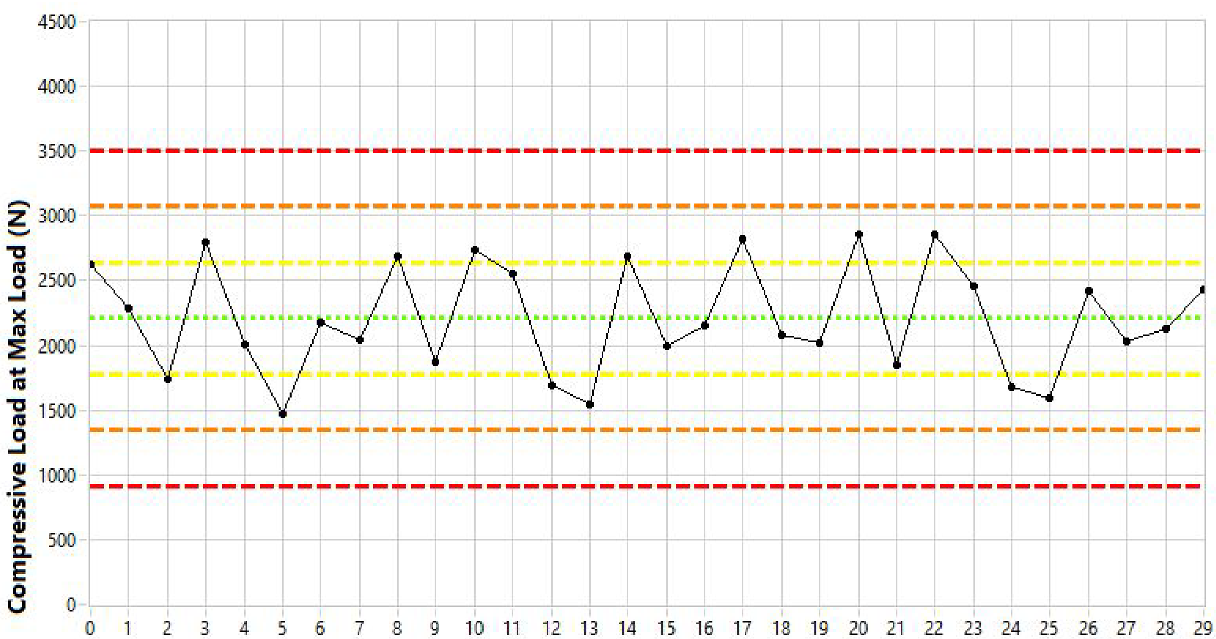

Figure 32. Disc splitting compressive load at max load (N), mean = 2210, standard deviation = 431.

10.0 RE-MACHINED SPECIMEN DIFFUSIVITY

Thermal diffusivity values are collected from the re-machined tensile specimens per ASTM E1461-07.[15] Diffusion of heat through the specimen following application of thermal energy via a laser source demonstrates heat transfer characteristics and can be used to calculate thermal conductivity for design purposes. The resulting group of diffusivity values, revealing a tight grouping of thermal transfer characteristics, is shown in Figure 33.

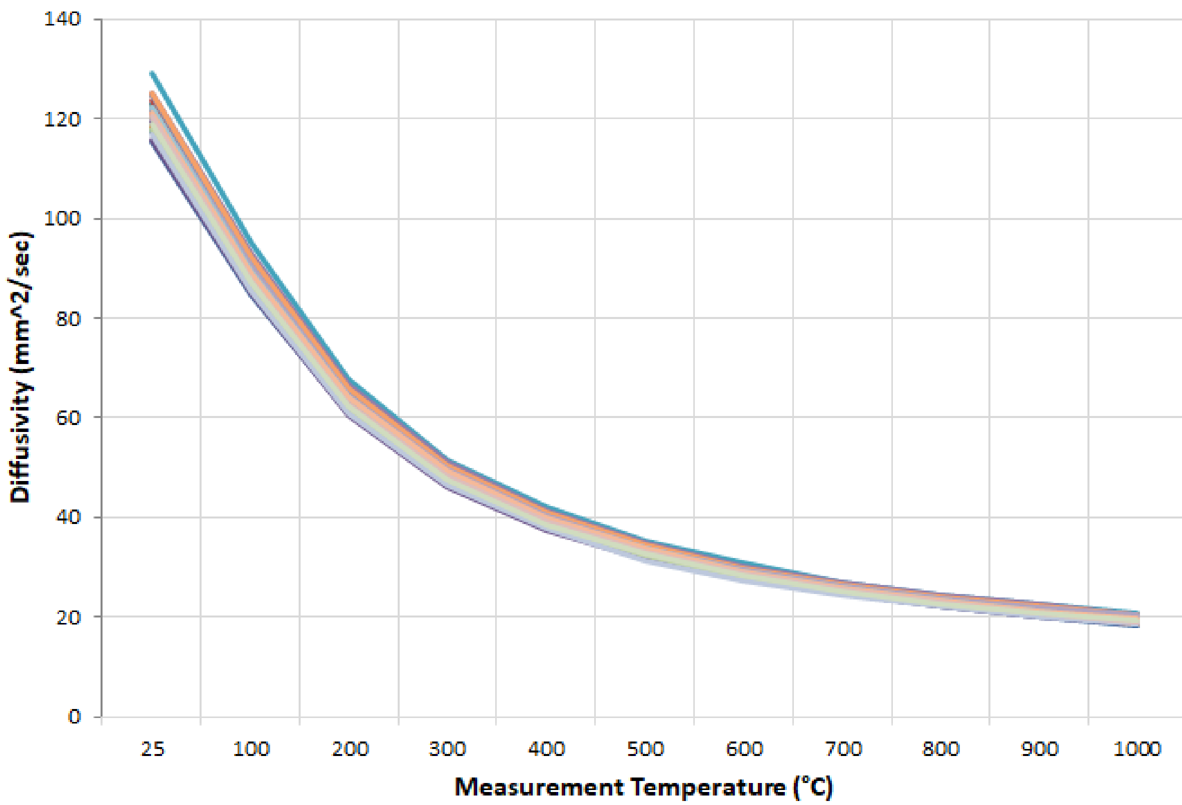

Figure 33. Re-machined specimen diffusivity.

11.0 SUMMARY

Comprehensive data sets for PCEA Billet 01S8-9 have been compiled into summary files of property scalar values. The data spreadsheet files are divided by mechanical test-specimen type into three main sets: (1) compressive, (2) flexural, and (3) tensile. The multitude of tests and evaluations performed on each specimen type are individually tabbed in the main data-set files.

In addition to a full visual review of the data files to determine whether obvious errors were made with the data collected (e.g., missing information or otherwise blank cells), graphical representations were made of individual evaluations to provide a means to spot anomalies. A review of the data indicates that the files, as submitted, are fully representative of the measured properties of the graphite billets being tested, as outlined in the applicable test procedures and program plans.

12.0 REFERENCES

1. PLN-2497, "Graphite Technology Development Plan," Rev. 1, October 4, 2010.

2. PLN-3348, "Graphite Mechanical Testing," Rev. 4, March 16, 2017.

3. PLN-3467, "Baseline Graphite Characterization Plan: Electromechanical Testing," Rev. 2, June 22, 2015.

4. PLN-3267, "AGC-2 Characterization Plan," Rev. 0, March 19, 2010.

5. Mark Carroll, Joe Lord, and David Rohrbaugh, *Baseline Graphite Characterization: First Billet*, INL/EXT-10-19910, September 2010.

6. LWP-20000-01, "Conduct of Research Plan," Rev. 0, August 2015.

7. Drawing 759143, "PCEA-Billet Plan 1 Baseline Graphite Characterization Slab and Sub Wedge Details," March 16, 2009.

8. Drawing 759293, "PCEA Billet 1 Baseline Graphite Characterization Standard Specimen Block and Specimen Sample Block Details," March 16, 2009.

9. ASTM C695-15, "Standard Test Method for Compressive Strength of Carbon and Graphite," ASTM International, 2015.

10. ASTM C769-09, "Standard Test Method for Sonic Velocity in Manufactured Carbon and Graphite Material for Use in Obtaining an Approximate Young's Modulus," ASTM International, 2009.

11. ASTM C747-93 (Reapproved 2005), "Standard Test Method for Moduli of Elasticity and Fundamental Frequencies of Carbon and Graphite Materials by Sonic Resonance," ASTM International, 2005.

12. ASTM C1259-08, "Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio for Advanced Ceramics by Impulse Excitation of Vibration," ASTM International, 2008.

13. ASTM C611-05, "Standard Test Method for Electrical Resistivity of Manufactured Carbon and Graphite Articles at Room Temperature," ASTM International, 2005.

14. ASTM E228-06, "Standard Test Method for Linear Thermal Expansion of Solid Materials with a Push Rod Dilatometer," ASTM International, 2006.

15. ASTM C559-90 (Reapproved 2005), "Standard Test Method for Bulk Density by Physical Measurements of Manufactured Carbon and Graphite Articles," ASTM International, 2005.

16. ASTM C651-91 (Reapproved 2005), "Standard Test Method for Flexural Strength of Manufactured Carbon and Graphite Articles Using Four-Point Loading at Room Temperature," ASTM International, 2005.

17. ASTM C749-08, "Standard Test Method for Tensile Stress-Strain of Carbon and Graphite," ASTM International, 2008.

18. ASTM E1461-07, "Standard Test Method for Thermal Diffusivity by the Flash Method," ASTM International, 2007.

Appendix A

Additional Compression-Specimen Database Plots (PCEA 01S8-9)

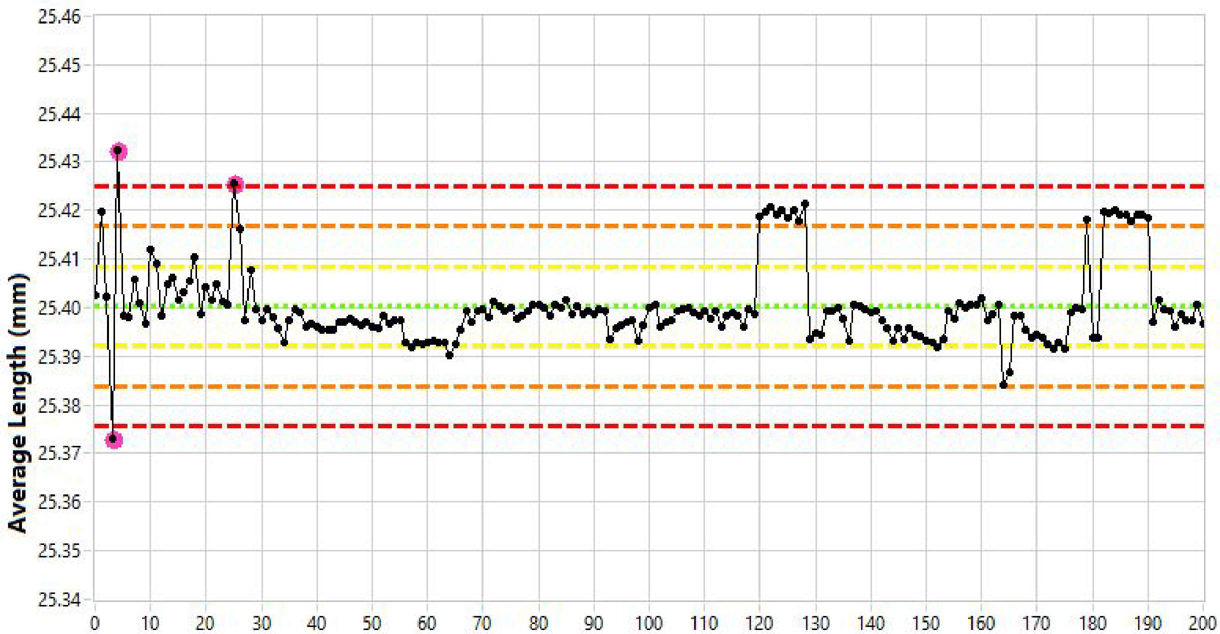

Figure A-1. Average length (mm), mean = 25.4003, standard deviation = 0.0082.

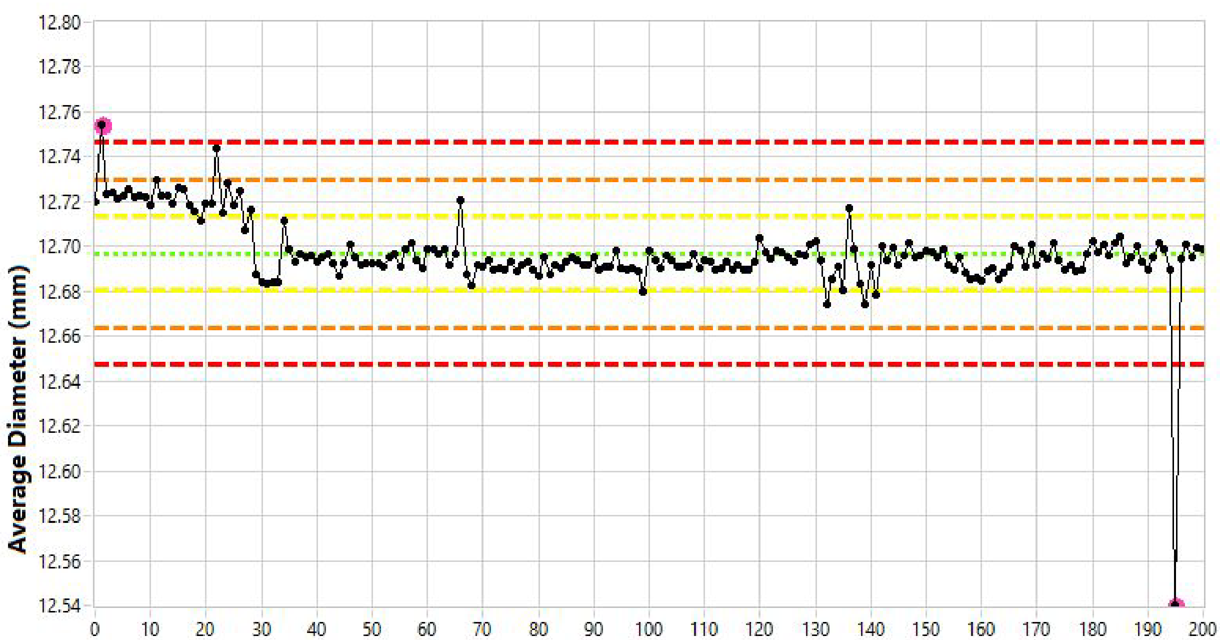

Figure A-2. Average diameter (mm), mean = 12.6970, standard deviation = 0.0165.

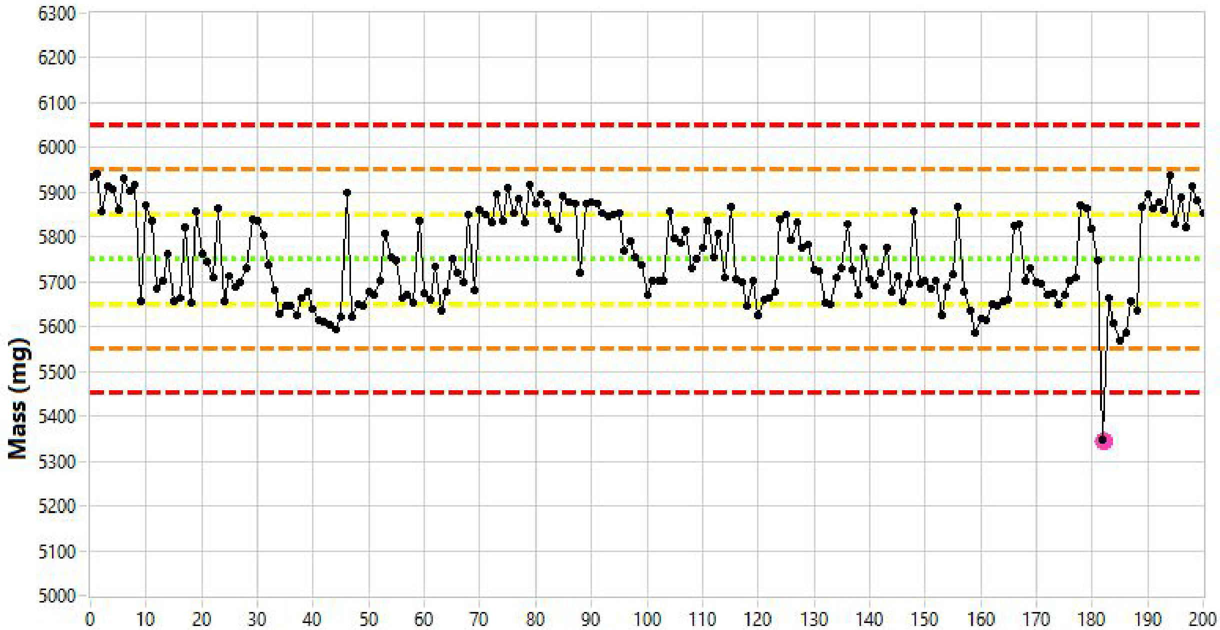

Figure A-3. Mass (mg), mean = 5751.2, standard deviation = 99.6.

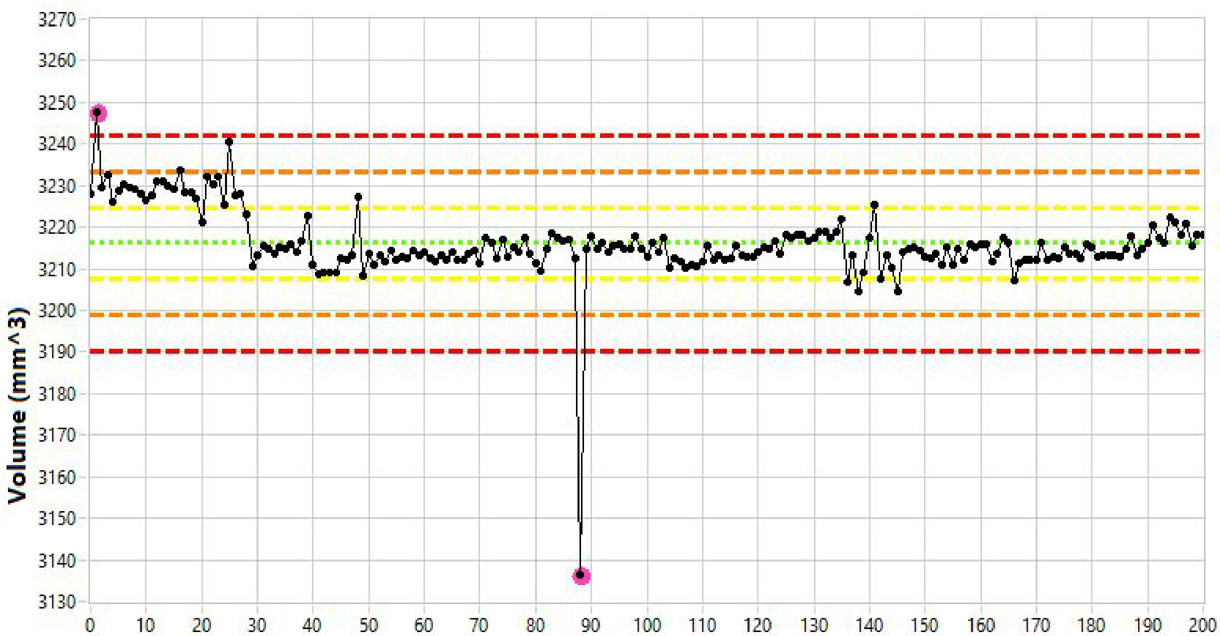

Figure A-4. Volume (mm^3), mean = 3216.1, standard deviation = 8.6.

Appendix B

Additional Flexural Specimen Database Plots (PCEA 01S8-9)

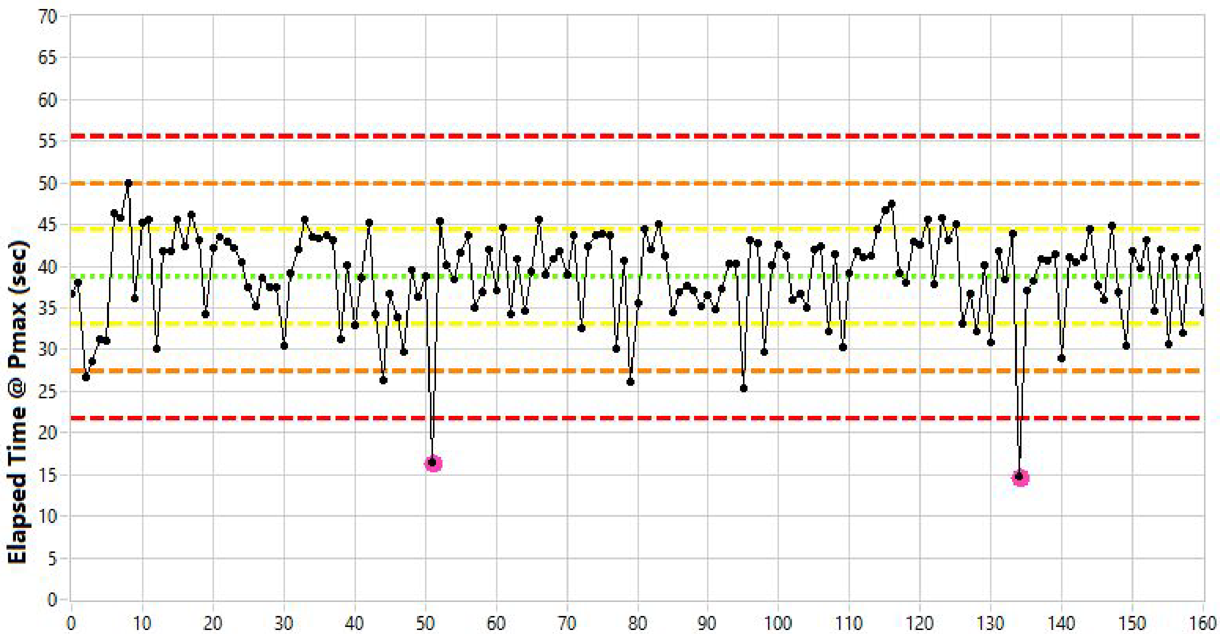

Figure B-1. Elapsed time at max load (sec), mean = 38.7, standard deviation = 5.6.

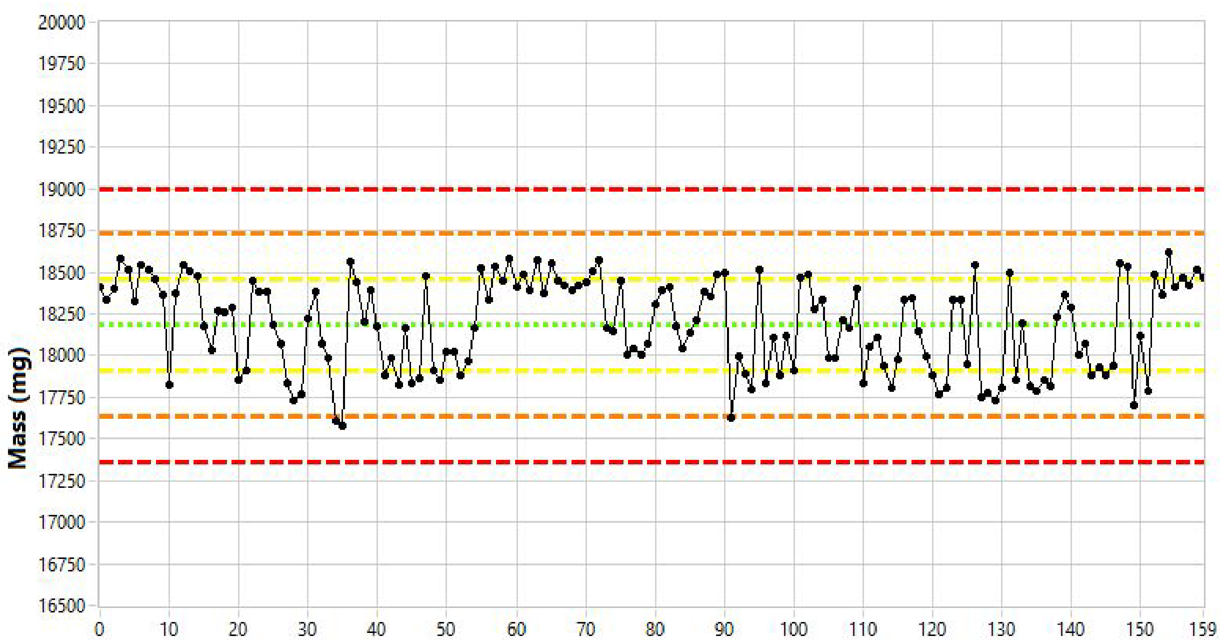

Figure B-2. Mass (mg), mean = 18181.4, standard deviation = 273.4.

Figure B-3. Volume (mm^3), mean = 10104.4, standard deviation = 7.7.

Appendix C

Additional Tensile Specimen Database Plots (PCEA 01S8-9)

Figure C-1. Modulus (automatic Young's) (GPa), mean = 8.8, standard deviation = 1.0.

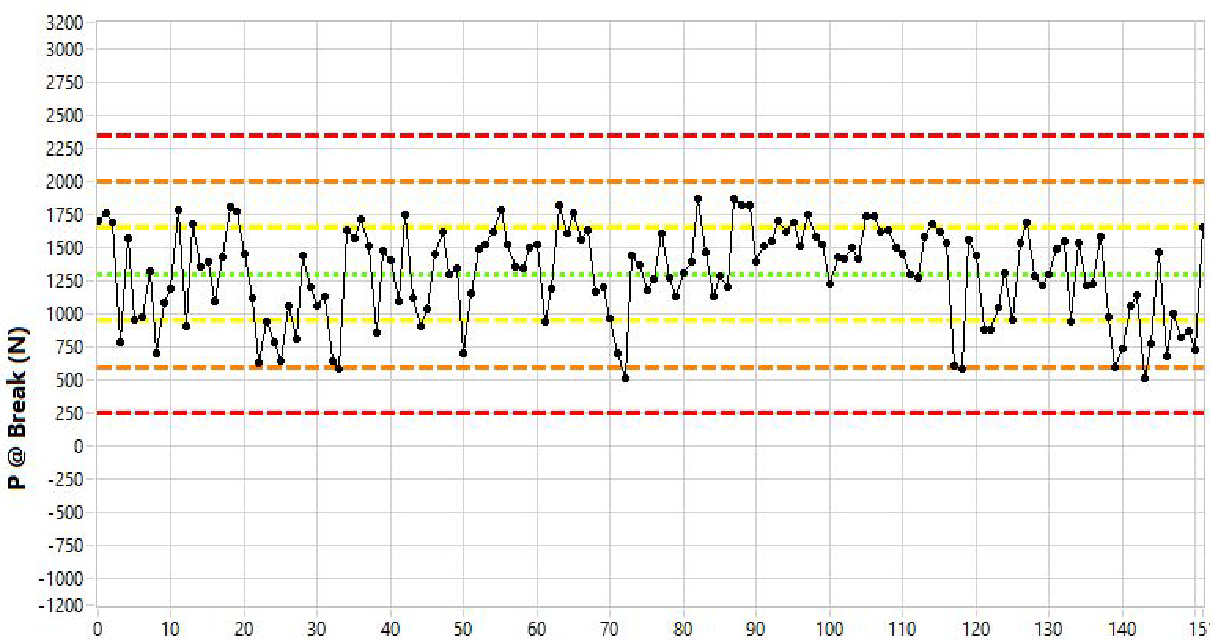

Figure C-2. Load at break (N), mean = 1299.1, standard deviation = 349.4.

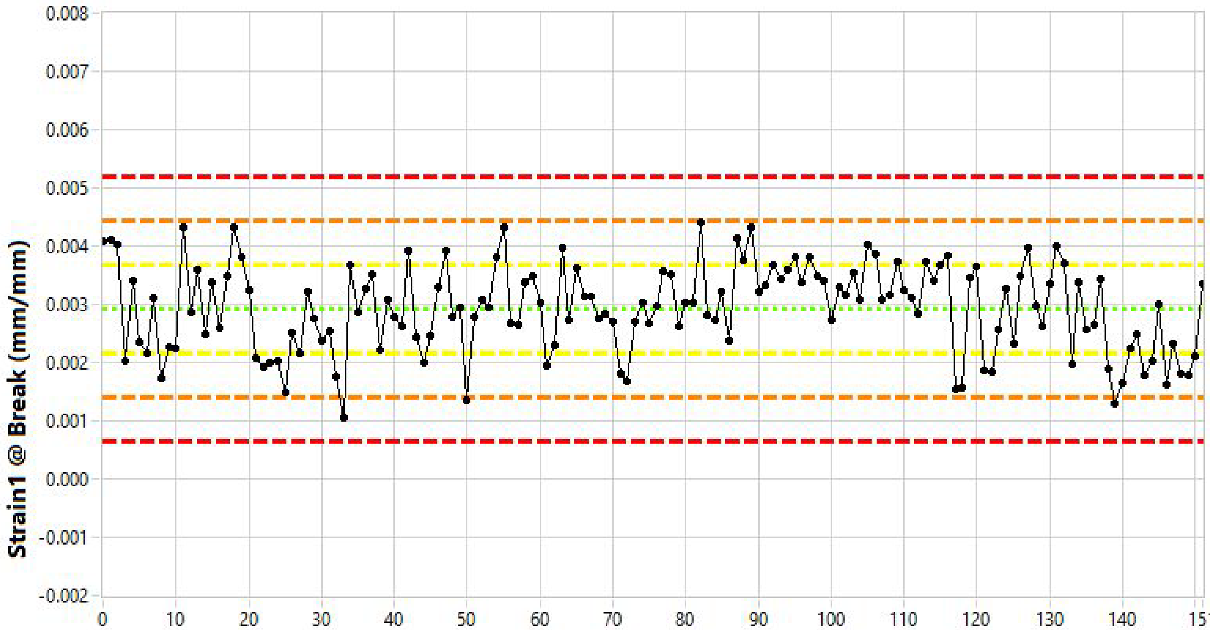

Figure C-3. Strain 1 at break (mm/mm), mean = 0.0029, standard deviation = 0.0008.

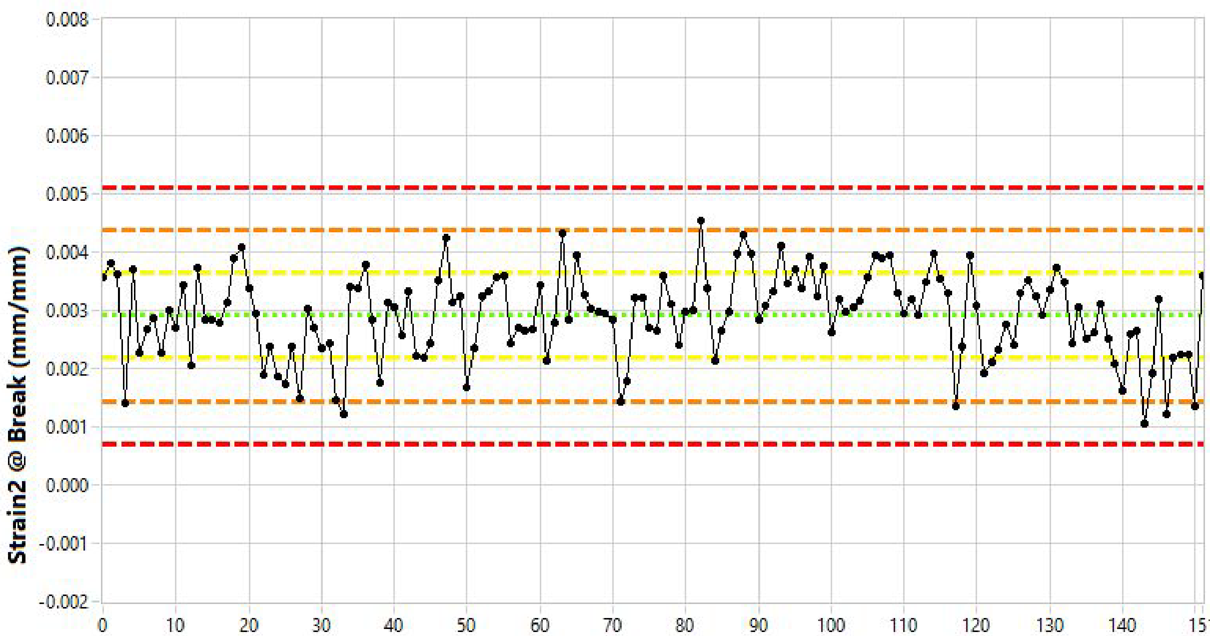

Figure C-4. Strain 2 at break (mm/mm), mean = 0.0029, standard deviation = 0.0007.

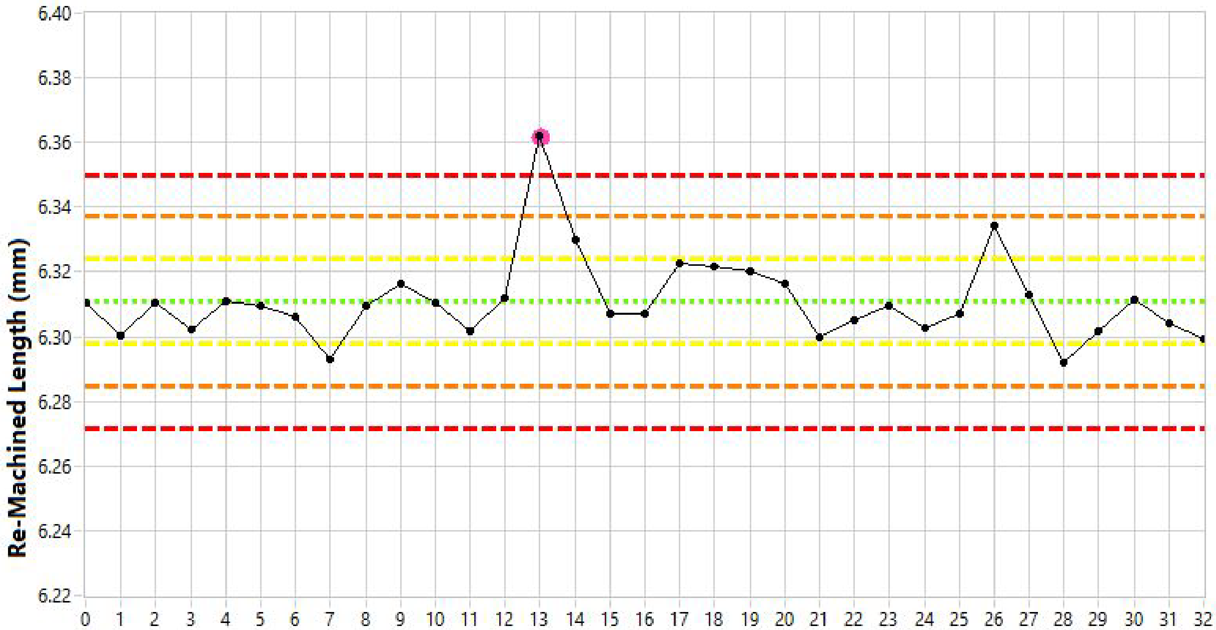

Figure C-5. Re-machined length (mm), mean = 6.3109, standard deviation = 0.0131.

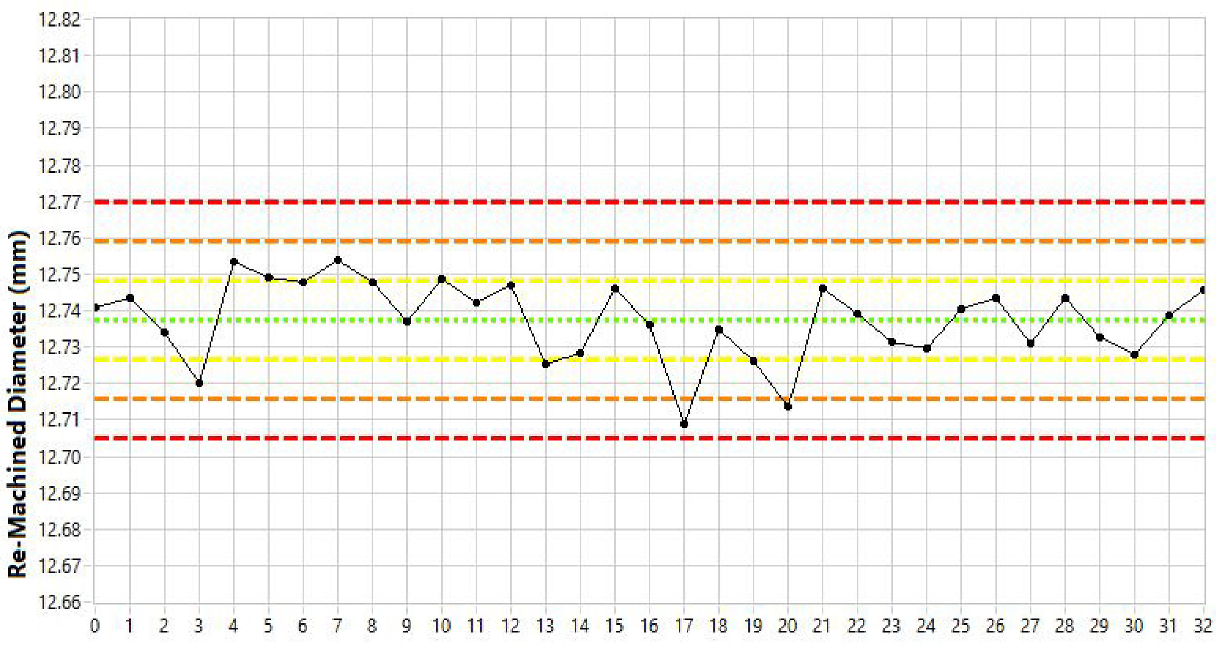

Figure C-6. Re-machined diameter (mm), mean = 12.7374, standard deviation = 0.0109.

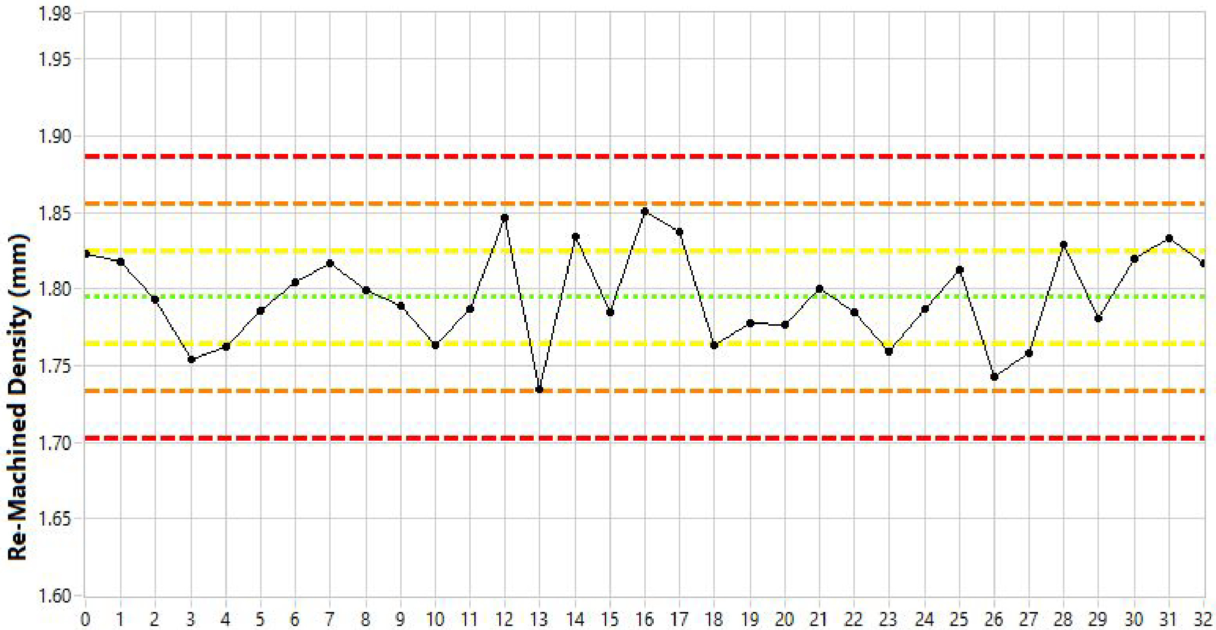

Figure C-7. Re-machined density (g/cm^3), mean = 1.7947, standard deviation = 0.0306.

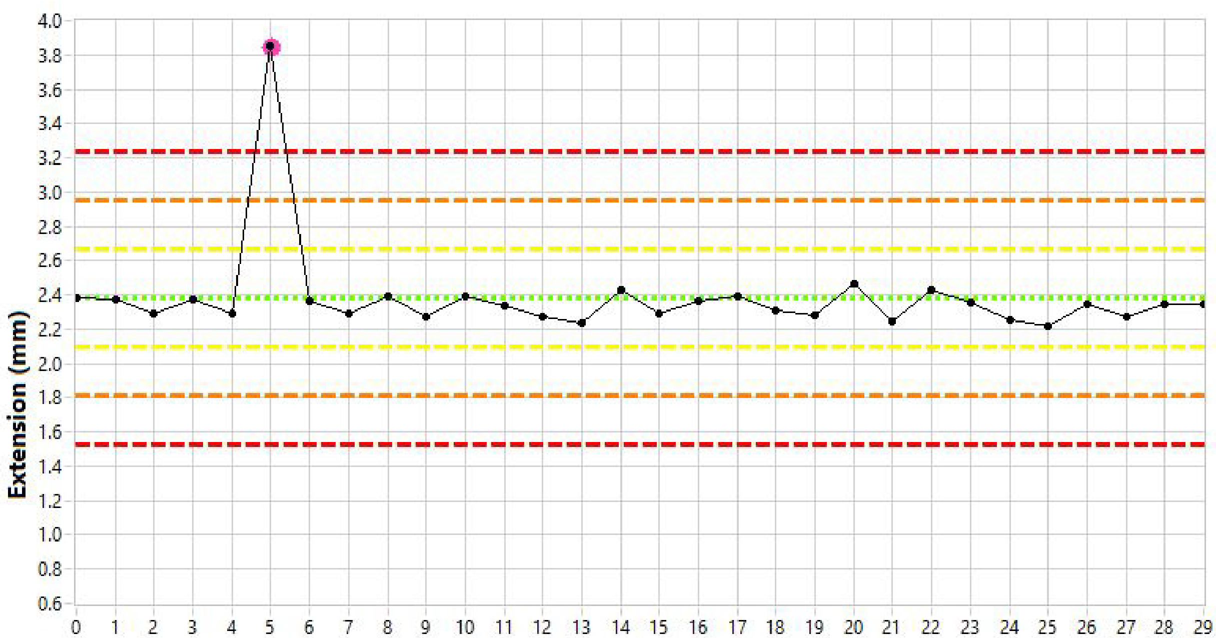

Figure C-8. Extension (mm), mean = 2.3813, standard deviation = 0.2845.

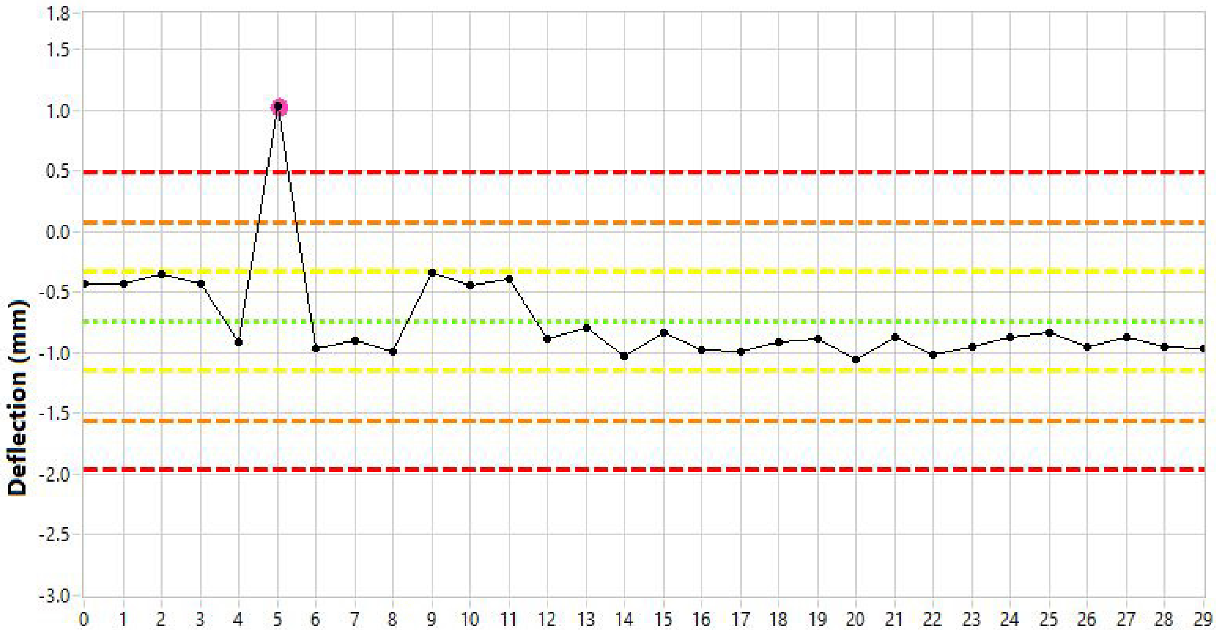

Figure C-9. Deflection (mm), mean = -0.7402, standard deviation = 0.4089.