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Mechanical Engineering Division
December 29, 2016

Ms. Phyllis Sevik
HEMI
Johns Hopkins University
3400 N. Charles Street, Malone Hall 147
Baltimore, MD 21218
Email: psevik@jhu.edu

Reference: SwRI® Project No. 18.22296: *Quasi-Static Compaction Characterization of Boron Carbide Powder*

Subject: Final Letter Report

Dear Ms. Sevik:

Please find enclosed the letter report which summarizes the work performed on the subject project. It has been a pleasure working with Johns Hopkins on this project and I look forward any collaborations we may have in the future.

Please feel free to contact the undersigned at (210) 522-3698 or by email at schocron@swri.edu with any questions or comments.

Sincerely,

Sidney Chocron, Ph.D.
Manager
Computational Mechanics Section
Engineering Dynamics Department

APPROVED:

James D. Walker, Ph.D.
Director
Engineering Dynamics Department

cc: A. Tonge (ARL)
A. Carpenter
N. Scott
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1. Introduction

The purpose of this investigation was to perform confined compression tests on a boron carbide (B_4C) powder similar to that used to fabricate the baseline tiles used in the MEDE program. The tests were designed to measure the axial stress, hoop strains, confinement and hydrostatic pressures, and equivalent stresses within the powder material during compression. Similar tests were documented in SwRI Report 18.06188 (Ref. [1]), where the details of the procedure are reported. The provided data could be used to fit a material constitutive model such as Drucker-Prager in order to simulate the B_4C powder within a hydrocode or other finite element program.

Southwest Research Institute (SwRI) conducted six tests of the B_4C powder (and one pre-test used to assess the test setup). This report describes the materials and test methods used, the analysis of the raw data, and the results for the six tests.

2. Materials and Methods

2.1 B_4C Powder

The B_4C powder (3M® ESK Tetrabor 3000F) used in the tests reported below was provided to SwRI by ARL (Jerry LaSalvia). ARL reports that SEM images, see Figure 1, show that the powder has been spray dried with remains of some primary particles in the micron-size range. Approximately 0.4 g of powder was used during each test.

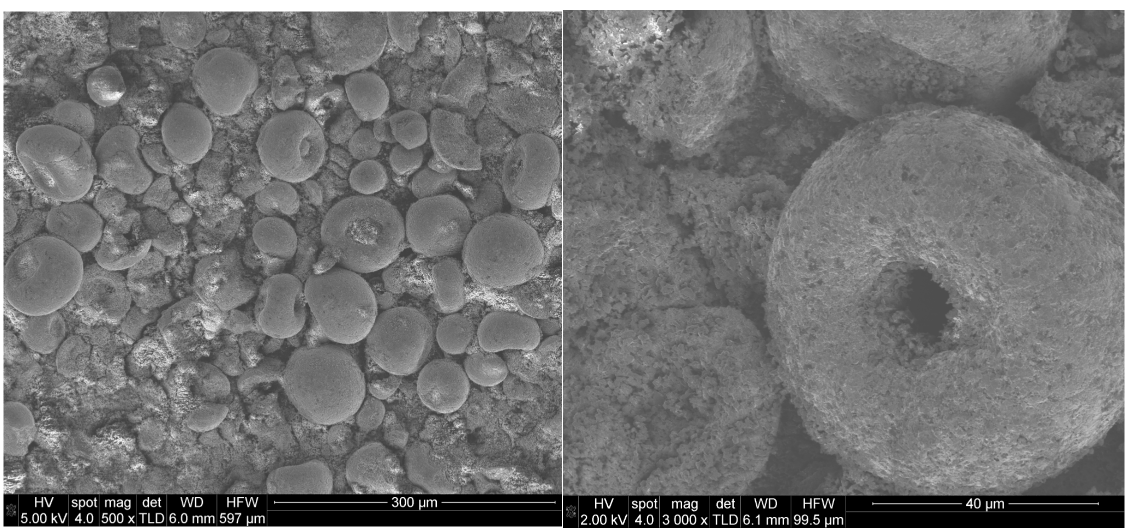

Figure 1. SEM images provided by ARL (Kristopher Behler)

2.2 Tungsten Carbide Anvils and Vascomax Sleeves

During each compression test, the powder was sandwiched between two tungsten carbide anvils. These anvils, measuring 6.27 mm (0.274 in) in diameter, were manufactured and provided by Micro Precision, Inc. of San Clemente, CA. The parallelism tolerance of the anvil faces was specified as 0.01 mm in order to maintain even loading of the powder during the tests. Drawings for the anvils are provided in Appendix A.

A Vascomax C350 maraging steel sleeve surrounded the powder during each test to provide the necessary confinement. The sleeves were machined from 12.7-mm (0.5-in) diameter rod stock. The inner diameter of the sleeves, 6.3 mm (0.248 in), was chosen to provide a tight clearance between the sleeves and the tungsten carbide anvils. Manufacture of the sleeves was performed by SwRI's Mechanical Fabrication Center. Drawings for the sleeves are also provided in Appendix A. A strain gage was attached to the outside surface of each sleeve prior to testing. These strain gages were oriented so as to measure the hoop strains on the sleeve surfaces during the tests.

2.3 Confined Compression Tests

Quasistatic confined compression tests were performed using an MTS servohydraulic load frame. A photograph of the setup for one of the tests is shown in Figure 2, while a labelled illustration of the configuration is presented in Figure 3. The powder was placed inside the Vascomax sleeve with a tungsten carbide anvil above and below. During the test, the MTS machine applied a compressive load to the anvils, which led to compaction of the powder. The powder was subjected to ever increasing loads during the test. Between loading cycles, the powder was fully unloaded, i.e. the axial load was reduced to 0. An MTS clip gage with a maximum travel of 0.2 in was placed on the setup to measure the relative displacement of the anvils during the tests.

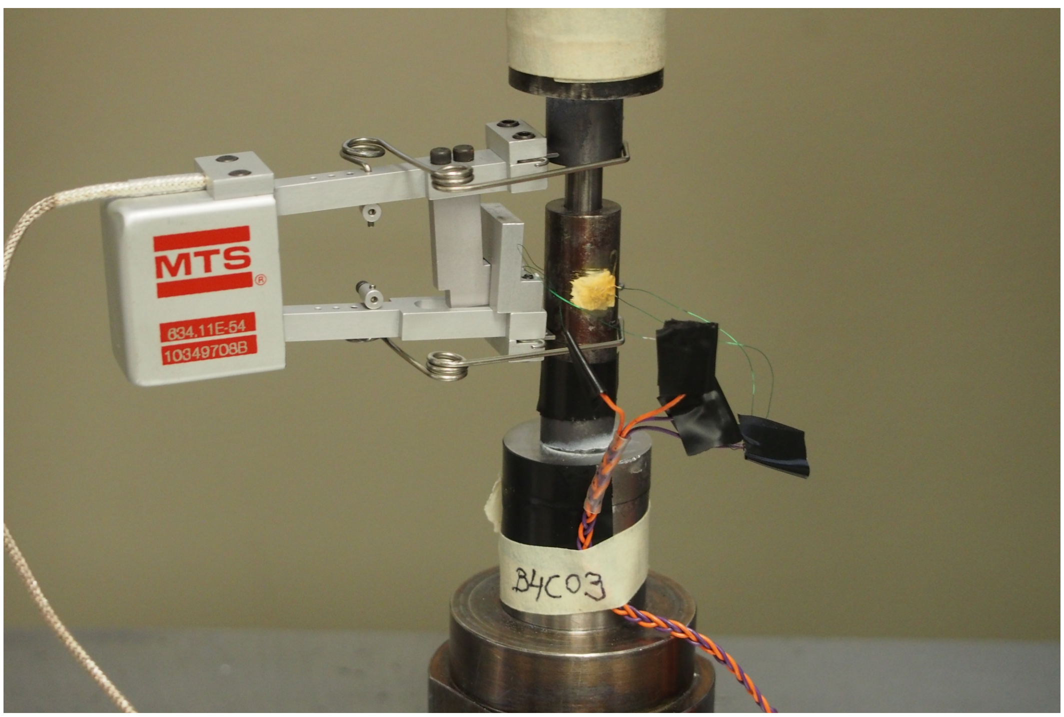

Figure 2. A photo of the test setup for specimen B4C-03 is shown.

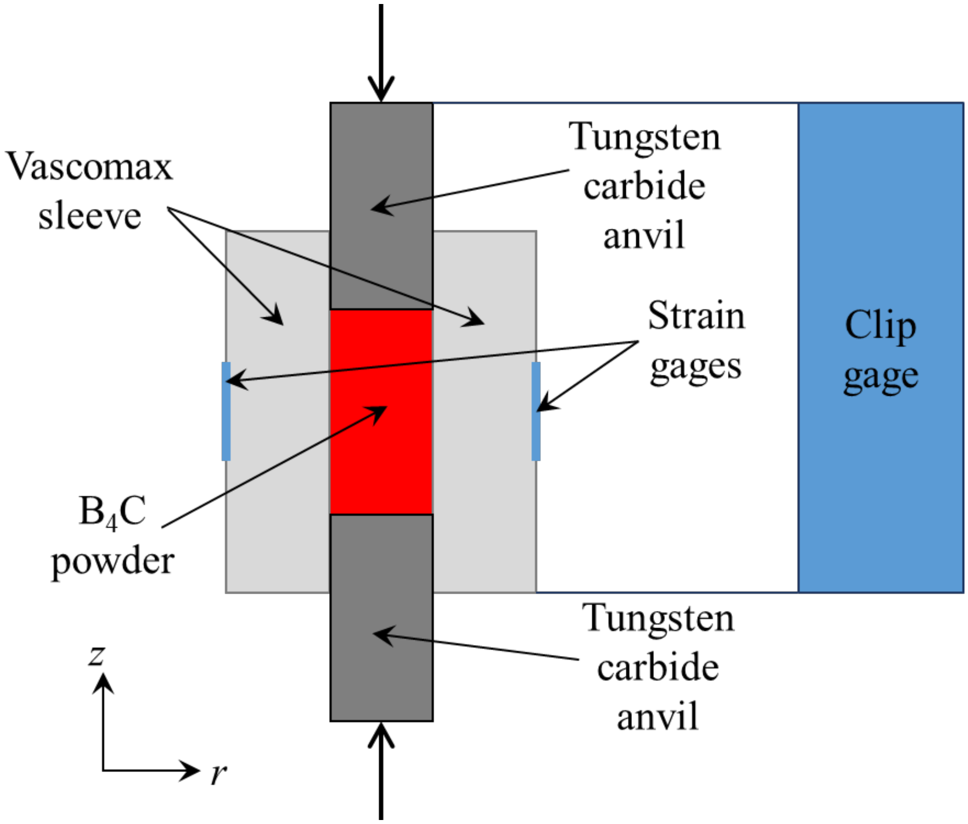

Figure 3. A schematic illustrating the cross-section of a confined compression test is shown.

Both the hydrostatic pressure, P, and the equivalent stress, σ_{eq}, at any time during the test can be calculated from the compressive load measured by the MTS machine and the hoop strain on the Vascomax sleeve surface, ε_{hoop}, which was measured by the strain gage. The compressive load was divided by the cross-sectional area of the powder to determine the axial stress, σ_z. The confinement pressure, P_c, was calculated using

$$P_c = \frac{E_{sleeve}}{2}\left(\frac{b^2 - a^2}{a^2}\right)\varepsilon_{hoop} \tag{1}$$

where a and b are the inner and outer radii of the Vascomax sleeve, respectively, and E_{sleeve} is the Young's modulus of the Vascomax material. The radial stress, σ_r, is equal to the negative of P_c. Finally, P and σ_{eq} were calculated by

$$P = -\frac{1}{3}(2\sigma_r + \sigma_z) \tag{2}$$

$$\sigma_{eq} = \left|\sigma_r - \sigma_z\right| \tag{3}$$

Note that Equations 2 and 3 assume that compressive stresses are negative; however, all stresses share the same sign during the tests, so the stresses are represented as positive in the results section so as to avoid superfluous negative signs.

The density of the B_4C powder could be calculated at any time during the test by dividing the mass of the powder by the current volume of the "test chamber," i.e. the region between the two anvils. This assumes that there is no significant gap between the powder and anvils at the time the calculation is performed.

3. Results and Discussion

3.1 B_4C Powder

Table 1 provides information on the tests conducted during this study. Specimen B4C-01 was used primarily to assess the test setup, and weaker alumina anvils were used during the test to compress the powder. The data from this test is not considered in the remainder of this report. The other six specimens (B4C-02 through B4C-07) were used to conduct the six tests called for in the statement of work.

Table 1. Summary of Tests

Specimen	Powder Weight (g)	Initial Length (cm)	Post-Test Length (cm)	Anvil Type
B4C-01	0.396	1.20	0.70	Alumina
B4C-02	0.430	1.30	0.76	Tungsten carbide
B4C-03	0.380	1.12	0.66	Tungsten carbide
B4C-04	0.395	1.15	0.65	Tungsten carbide
B4C-05	0.404	1.17	0.71	Tungsten carbide
B4C-06	0.409	1.16	0.70	Tungsten carbide
B4C-07	0.399	1.14	0.67	Tungsten carbide

The axial stresses and hoop strains from the six tests are shown in Figures 4 and 5, respectively. One interesting characteristic of the tests is that during the unloading stages of each test, the axial stress returns to 0, but a positive residual hoop strain persists in the Vascomax sleeve. Given the range of measured strains and the high strength of the sleeve material, the sleeve is not expected to yield. In a previous project [2] the sleeve was estimated to yield when the outer hoop strain reaches 0.3%, almost one order of magnitude larger than the strains seen in the tests performed on the B_4C powder. Instead, it is thought that the B_4C powder "locks" within the sleeve during compression. When the axial load is removed, the powder expands slightly, but not enough to fully eliminate the radial load on the surrounding sleeve.

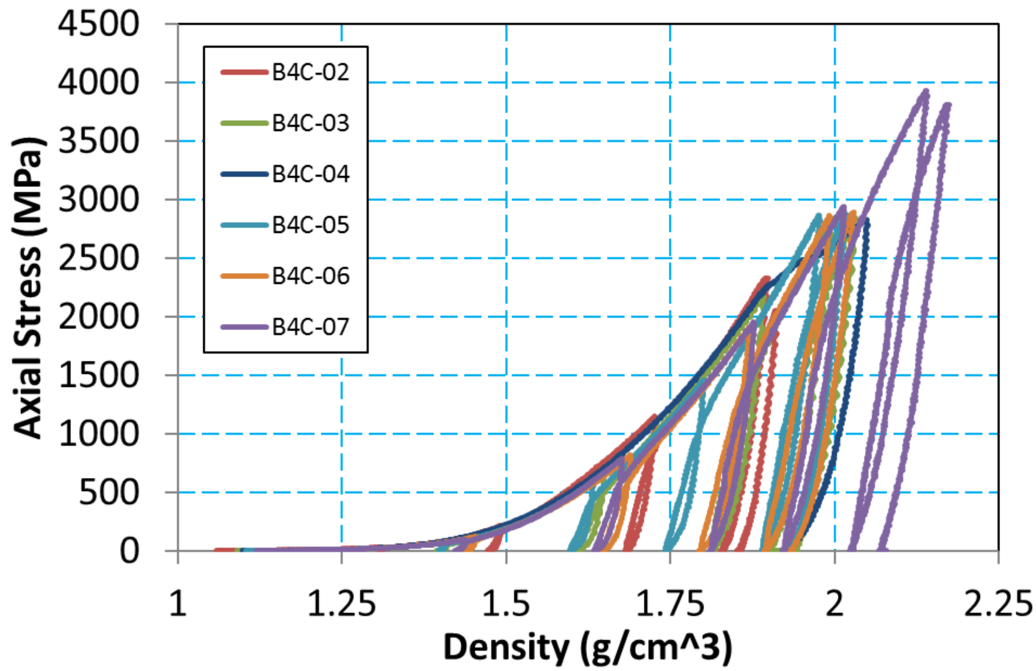

Figure 4. Axial stress is plotted against powder density for the confined compression tests.

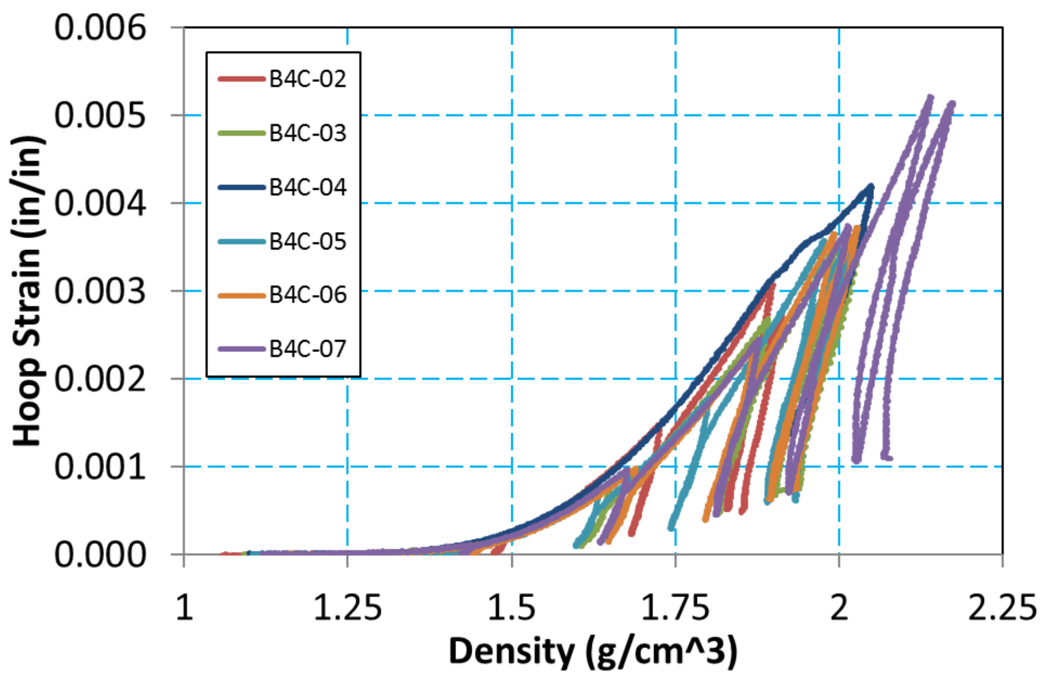

Figure 5. Hoop strain is plotted against powder density for the confined compression tests.

Figure 6 shows the resulting equivalent stress versus pressure curves for the B_4C powder. Except for test B4C-04, which exhibits a slight anomalous decrease in equivalent stress as compared to the other tests, there does not appear to be much variation between tests. Note that the upper bound of the envelope containing the equivalent stress-pressure curves is nearly equal to the line for which equivalent stress and pressure are equal, which is also shown in Figure 6. The B_4C powder appears to follow a relationship such that the equivalent stress required to plastically flow the material is equal to the current hydrostatic pressure. If there is an upper cap to this relationship, the data indicates that it does not occur below an equivalent stress of 2.3 GPa.

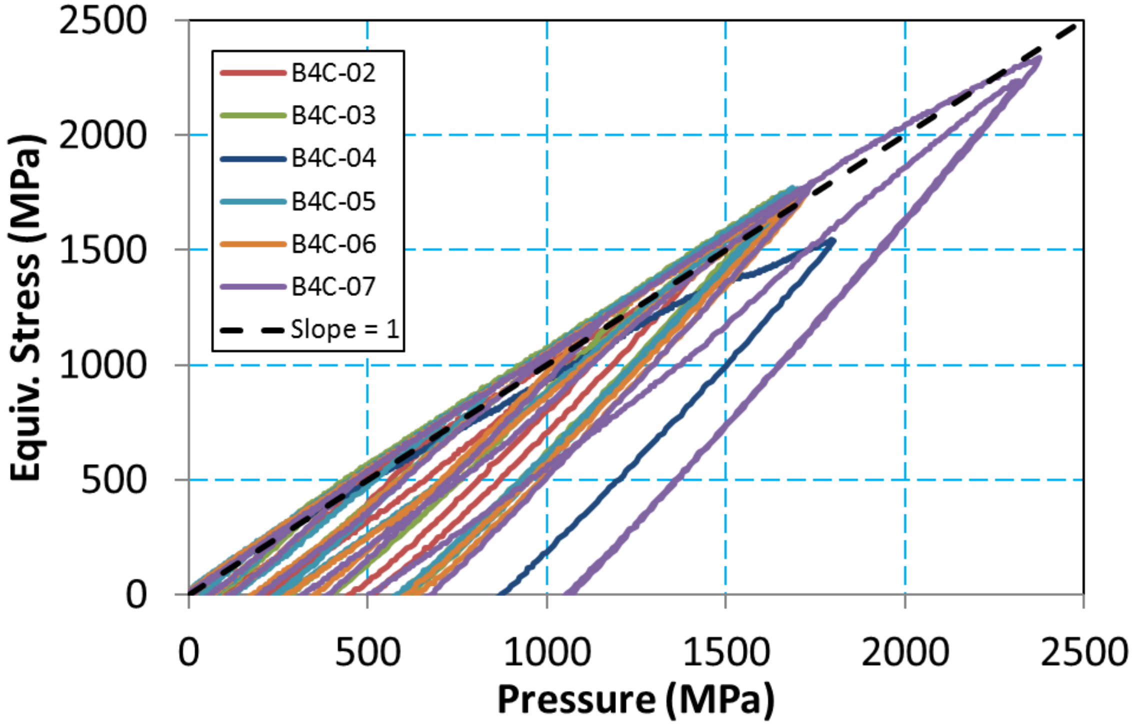

Figure 6. Equivalent stress is plotted against hydrostatic pressure for the confined compression tests.

Bibliography

[1] K. A. Dannemann, S. Chocron, A. E. Nicholls, J. D. Walker, and C. E. Anderson, "Ceramic Phenomenological Experiments - Compressive Strength of SiC. Southwest Research Institute Report no. 18.06188.," 2004.

[2] S. Chocron, C. E. Anderson, K. A. Dannemann, and A. E. Nicholls, "Characterization of borosilicate glass by confined compression testing and numerical validation.," 2009.

Appendix A: Drawings

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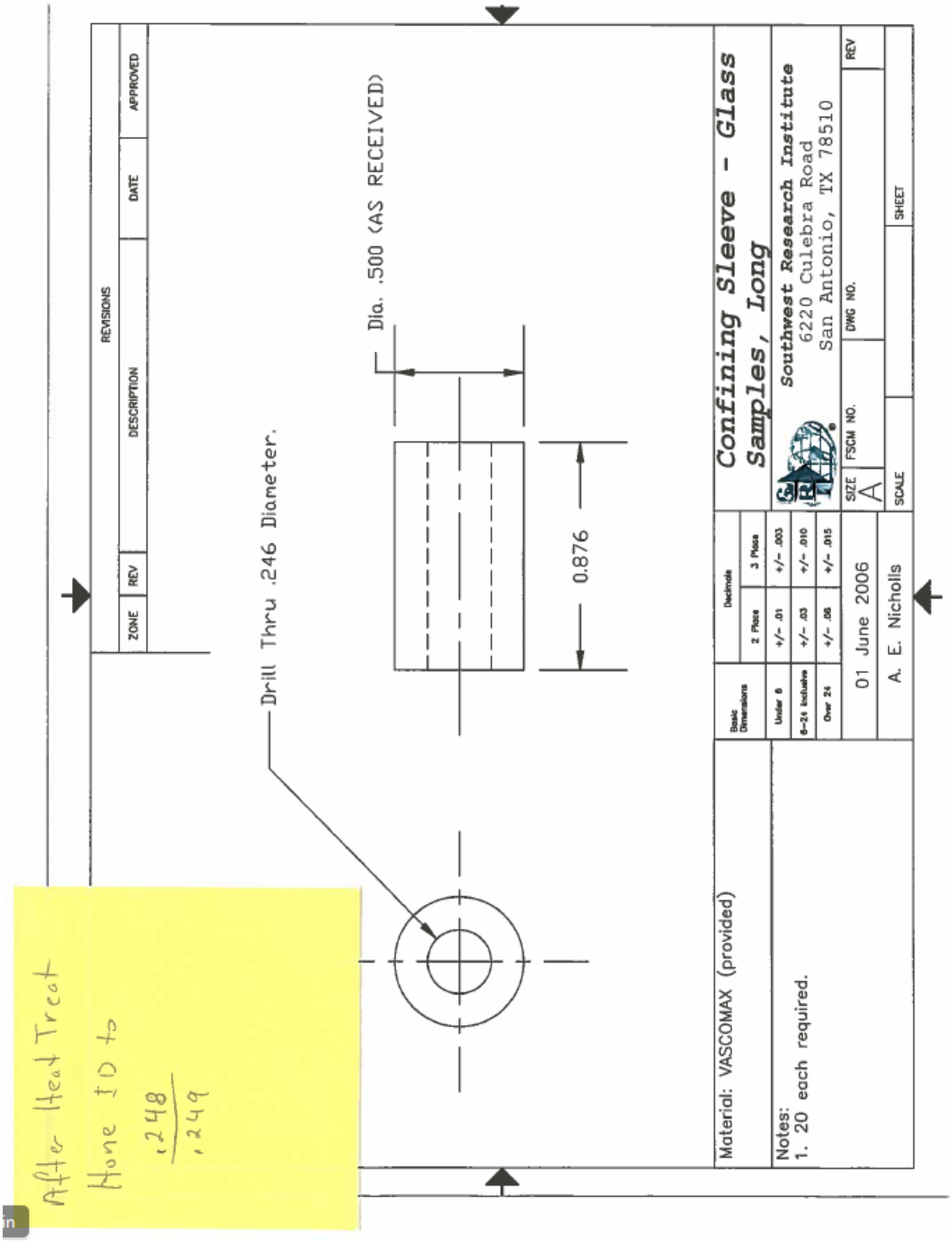
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ZONE
REV
DESCRIPTION
DATE
APPROVED
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Dia. .500 (AS RECEIVED)
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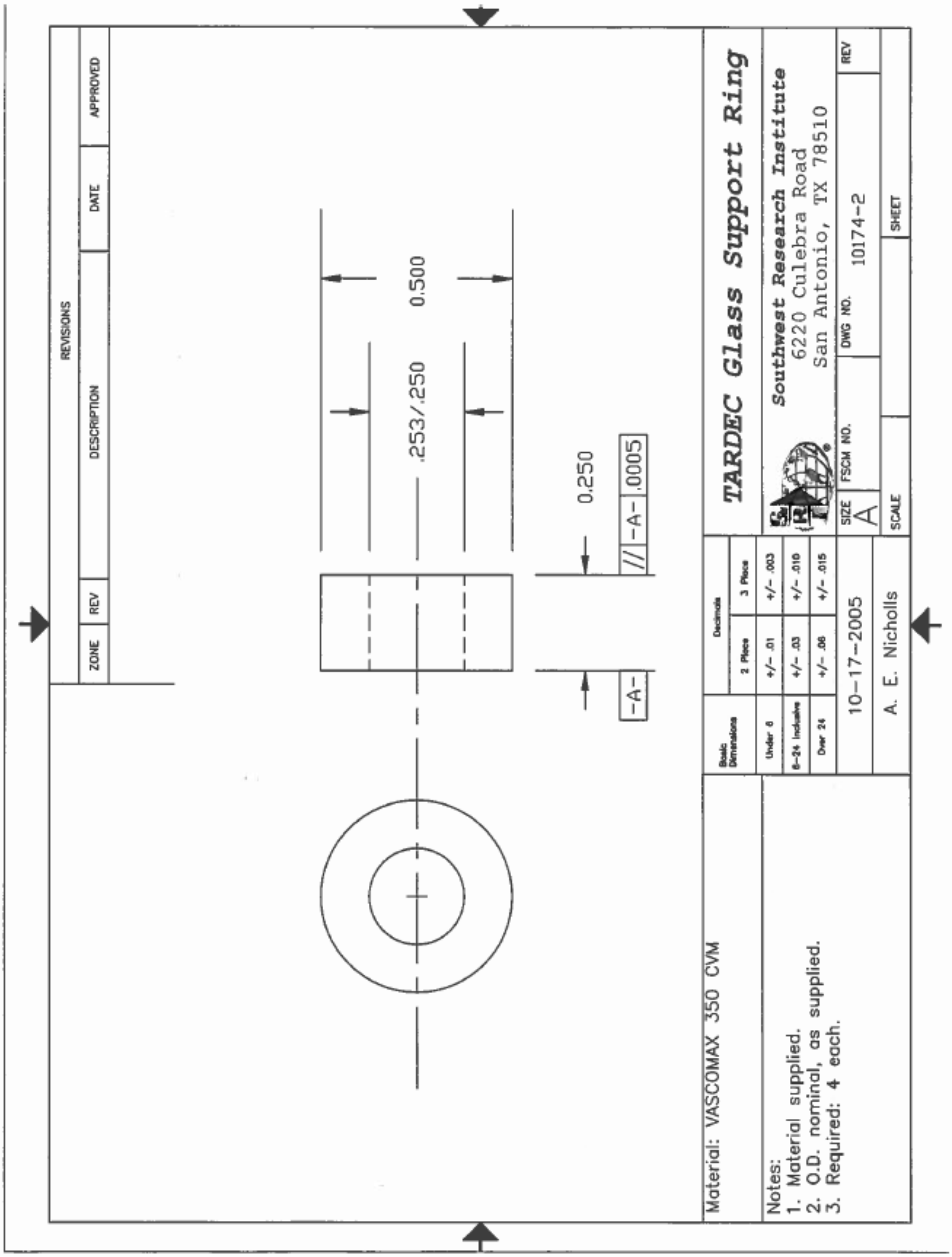
Notes:
1. 20 each required.
Basic Dimensions
Decimals
2 Place
3 Place
Under 6 +/- .01 +/- .003
6-24 Inclusive +/- .03 +/- .010
Over 24 +/- .06 +/- .015
01 June 2006
A. E. Nicholls
Confining Sleeve - Glass Samples, Long
Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78510
SIZE
A
FSCM NO.
DWG NO.
REV
SCALE
SHEET
After Heat Treat
Hone ID to
.248
.249


REVISIONS
ZONE
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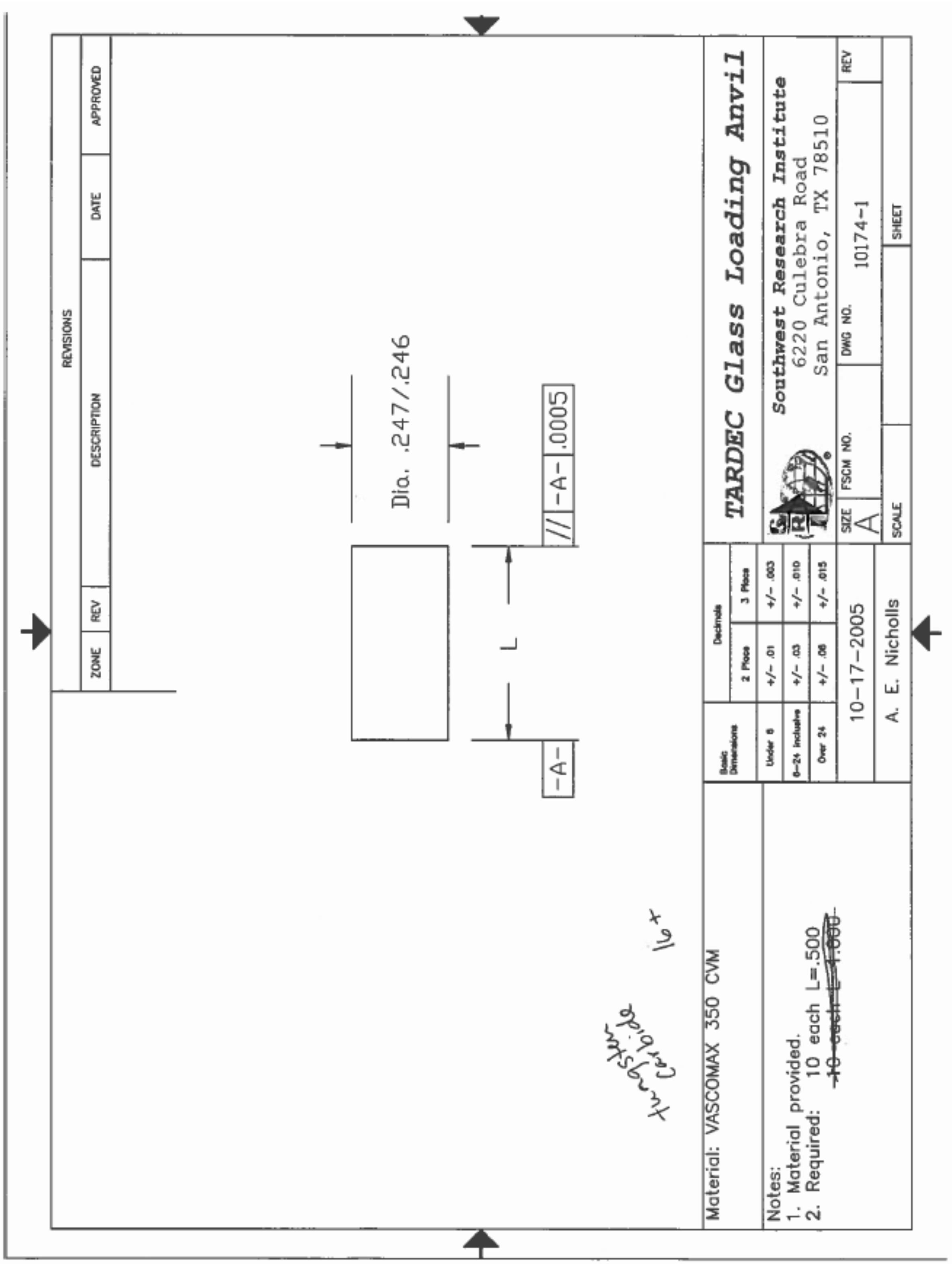
DESCRIPTION
DATE
APPROVED
0.500
.253/.250
0.250
-A-
// -A- .0005
Material: VASCOMAX 350 CVM
Notes:
1. Material supplied.
2. O.D. nominal, as supplied.
3. Required: 4 each.
Basic Dimensions
Decimals
2 Place
3 Place
Under 6
+/- .01
+/- .003
6-24 Inclusive
+/- .03
+/- .010
Over 24
+/- .06
+/- .015
10-17-2005
A. E. Nicholls
TARDEC Glass Support Ring
Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78510
SIZE
A
FSCM NO.
DWG NO.
10174-2
REV
SCALE
SHEET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ZONE
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DESCRIPTION
DATE
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Dia. .247/.246
L
-A-
// -A- .0005
Material: VASCOMAX 350 CVM
tungsten carbide
Notes:
1. Material provided.
2. Required: 10 each L=.500
Basic Dimensions
Decimals
2 Place
3 Place
Under 6 +/- .01 +/- .003
6-24 inclusive +/- .03 +/- .010
Over 24 +/- .06 +/- .015
10-17-2005
A. E. Nicholls
TARDEC Glass Loading Anvil
Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78510
SIZE
A
FSCM NO.
DWG NO.
10174-1
REV
SCALE
SHEET

Appendix B: Data from Individual Tests

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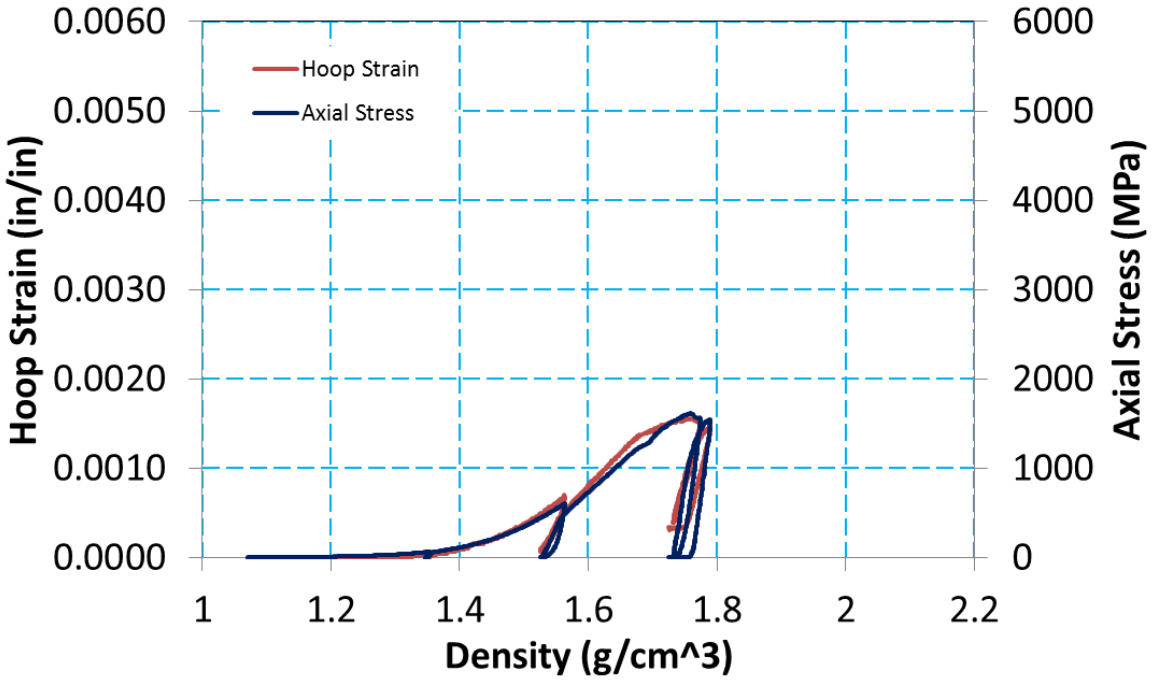
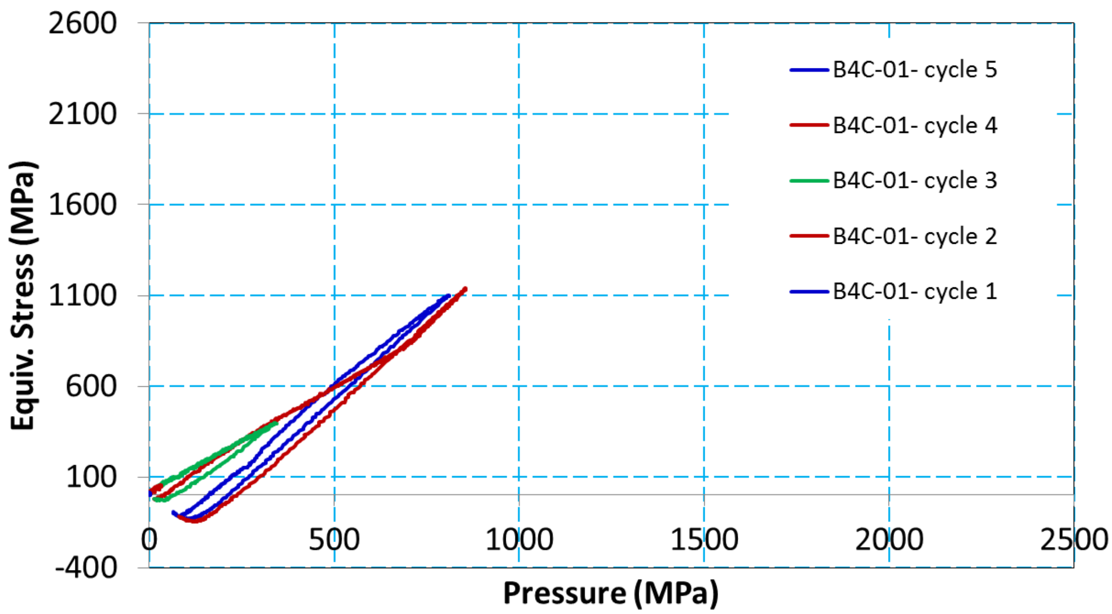
B4C-01

Weight: 0.396g

Initial Length: 0.473in

Post Length: 0.276in

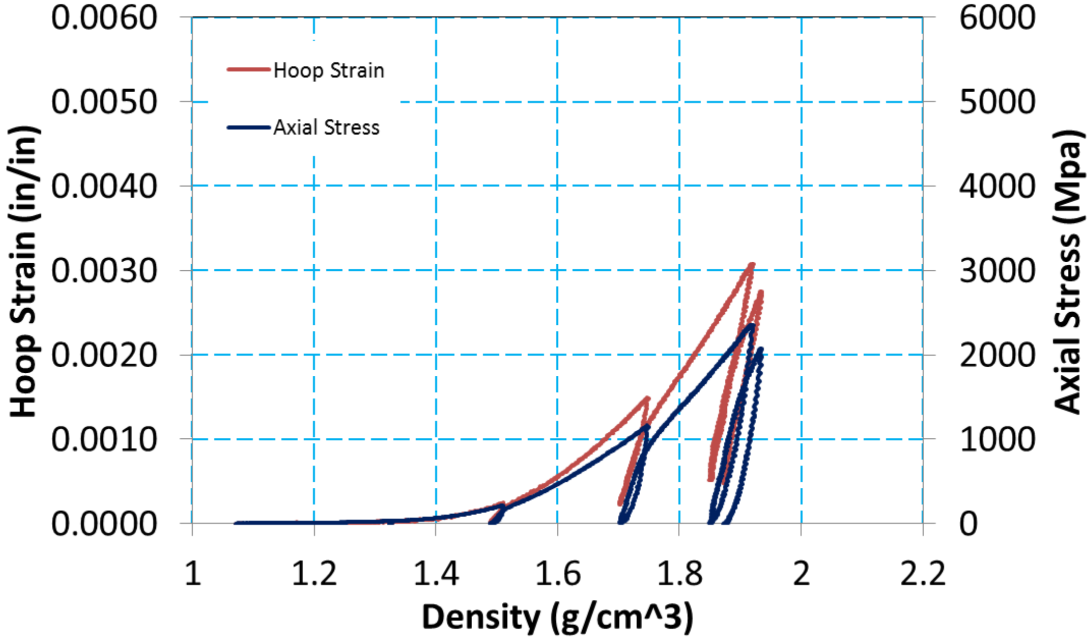


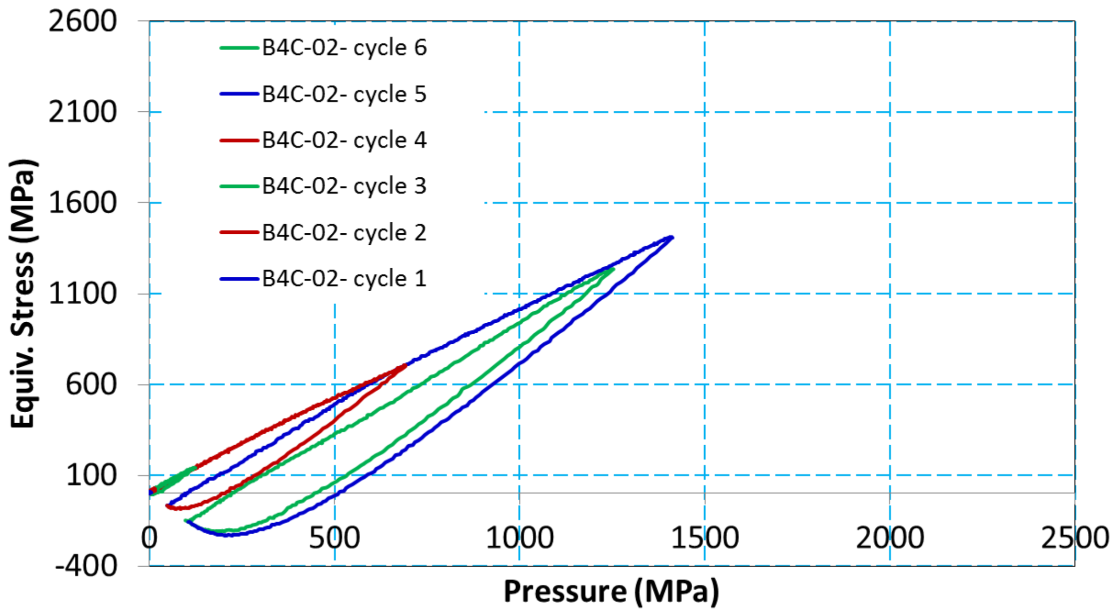


Note that in this and the following equivalent stress curves some of the values shown are negative. This is strictly incorrect because equivalent stress is, by definition, positive. Plotting $\sigma_{eq} = |\sigma_r - \sigma_z|$ cluttered the figure in a way that it was not possible to see the different load/unload cycles so, instead, what is being plot is $\sigma_{eq} = |\sigma_z| - |\sigma_r|$, which is the same when the absolute value of the z-stress is larger than the radial stress and the opposite when smaller.

B4C-02

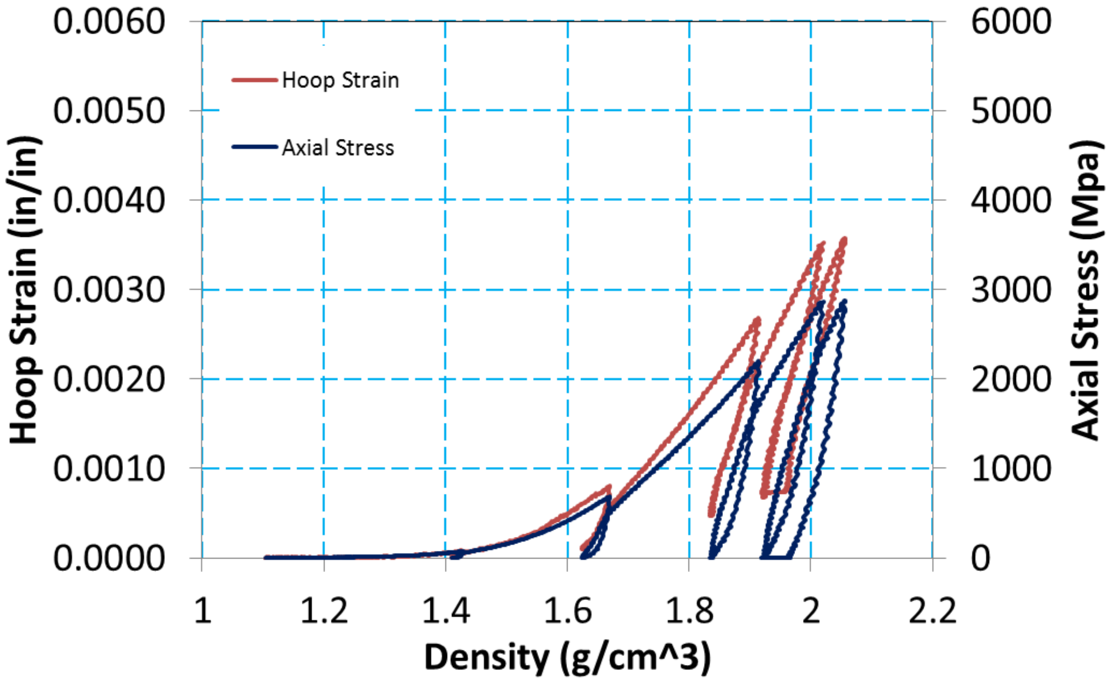
Weight: 0.430g
Initial Length: 0.513in
Post Length: 0.300in

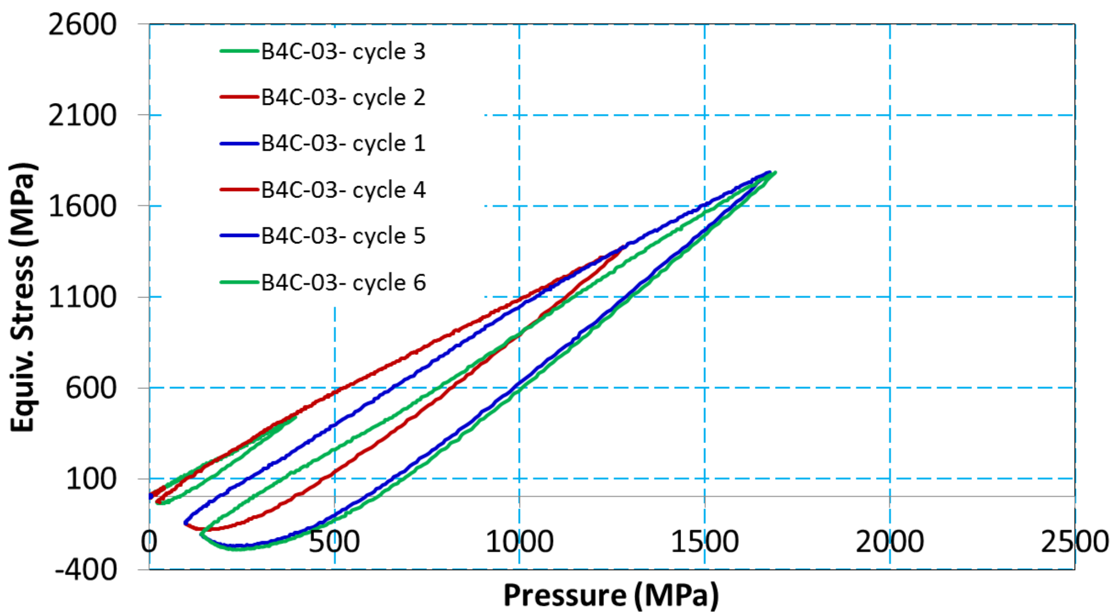




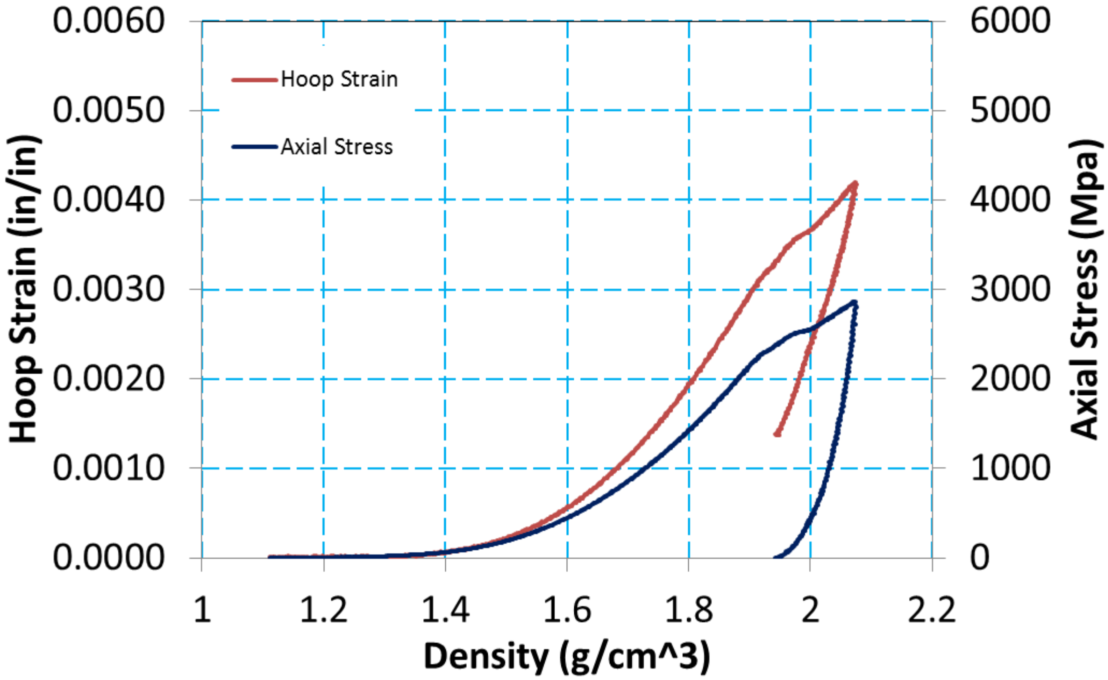
B4C-03

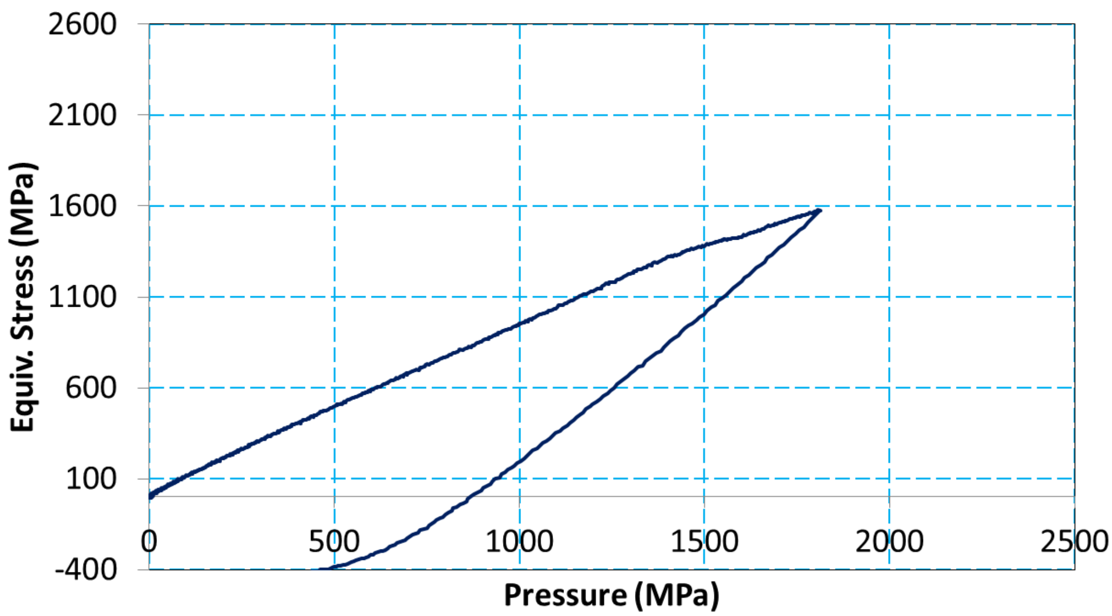
Weight: 0.380g
Initial Length: 0.440in
Post Length: 0.261in



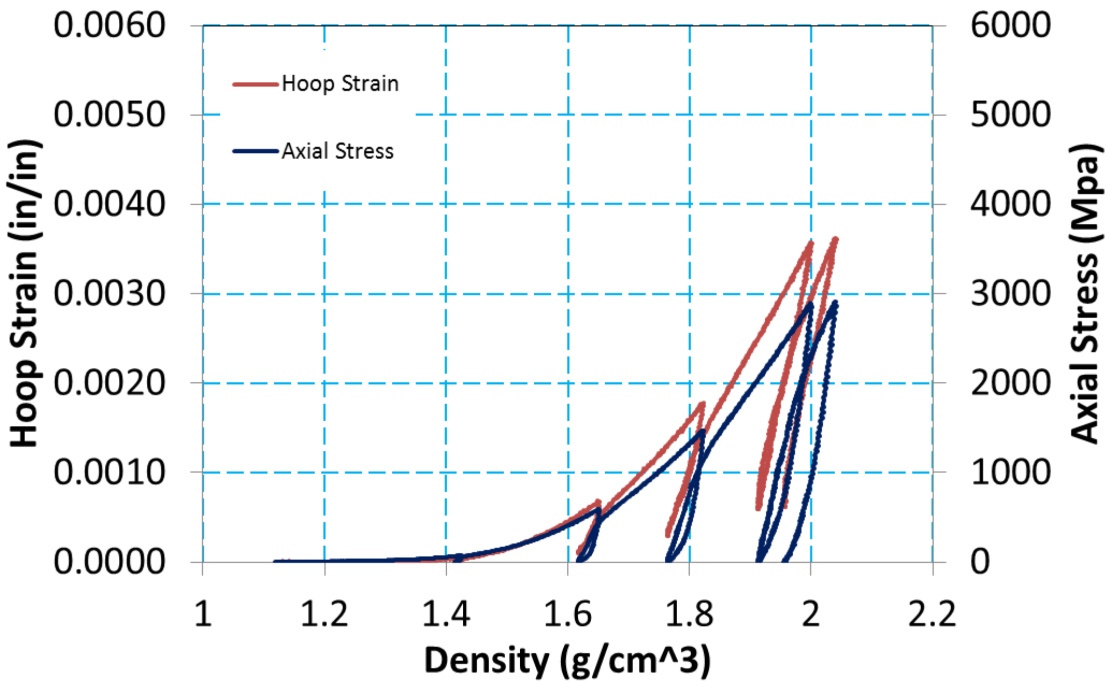


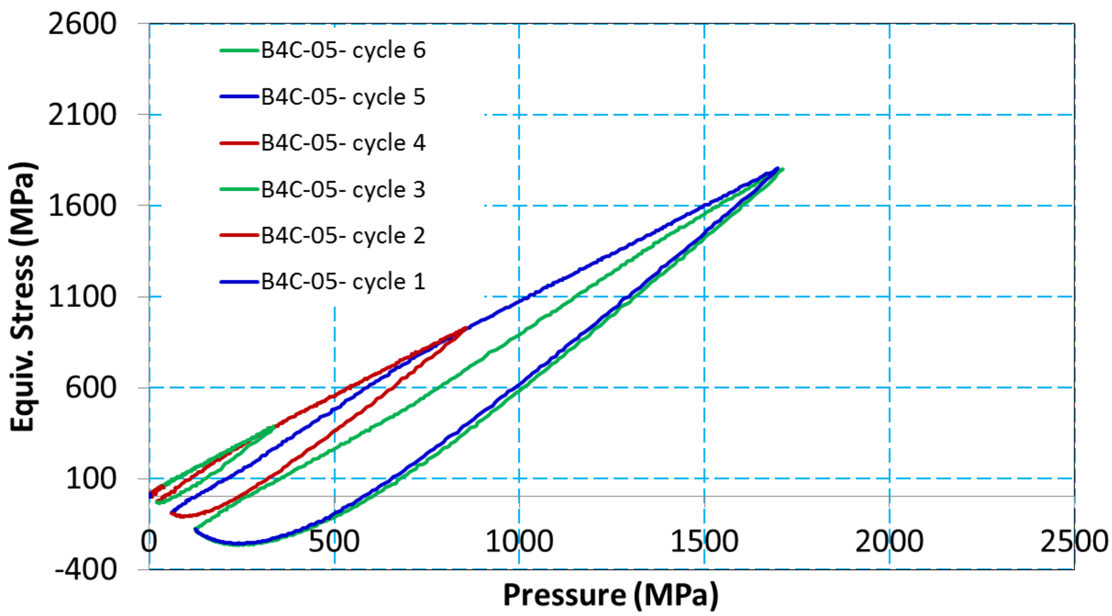
B4C-04
Weight: 0.395g
Initial Length: 0.454in
Post Length: 0.256in



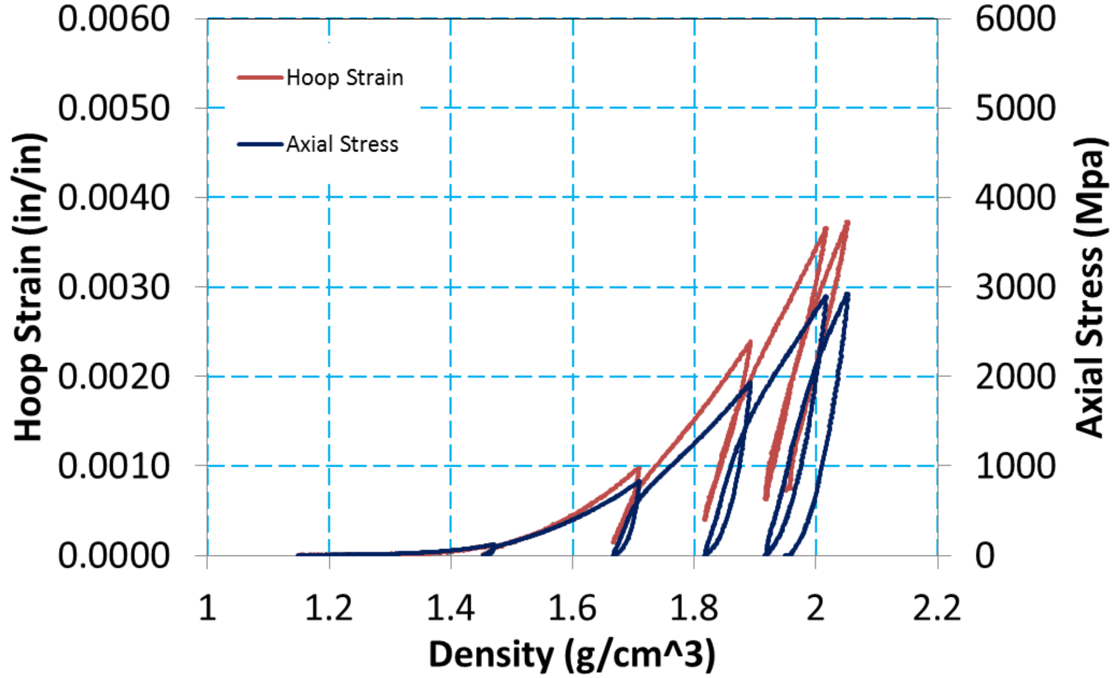


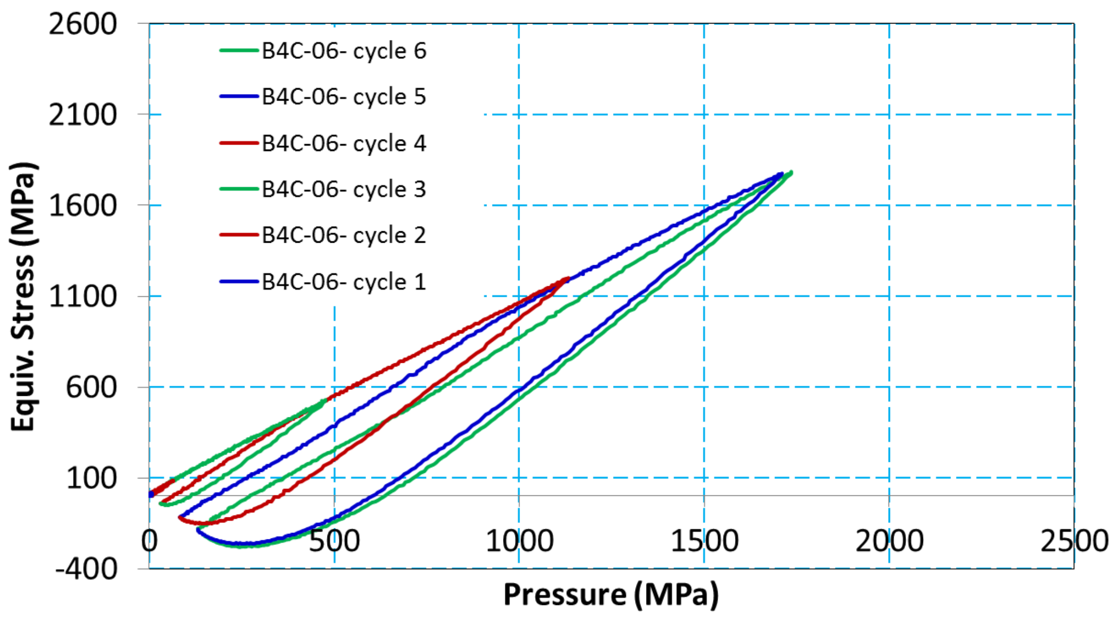
B4C-05
Weight: 0.404g
Initial Length: 0.462in
Post Length: 0.281in





B4C-06
Weight: 0.409g
Initial Length: 0.455in
Post Length: 0.276in



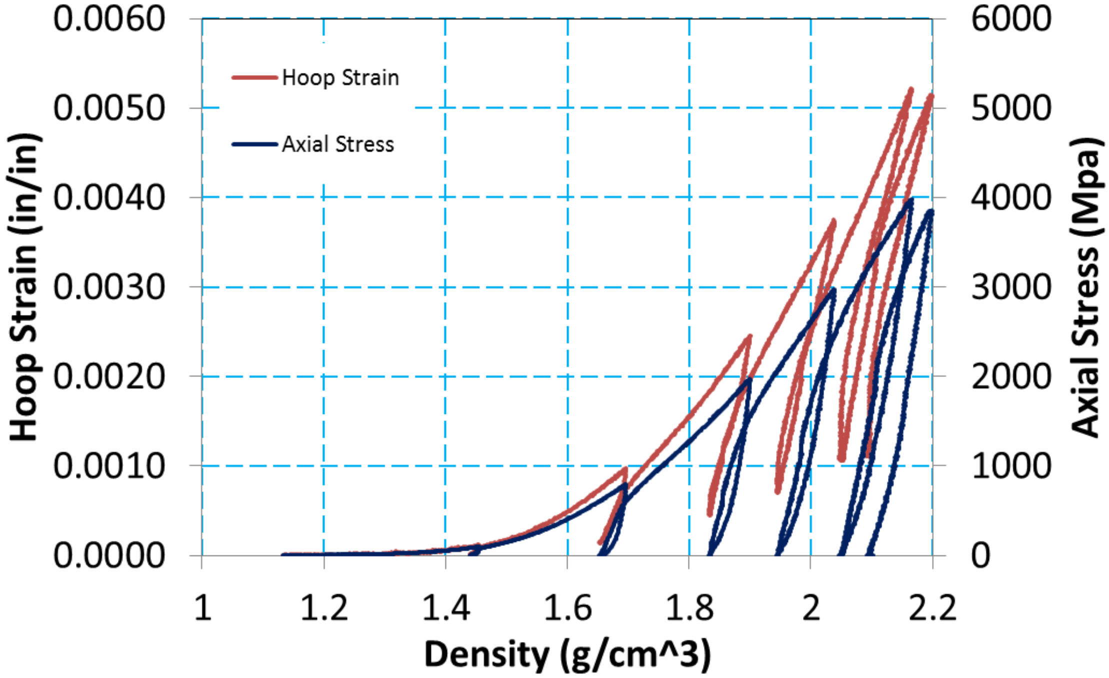


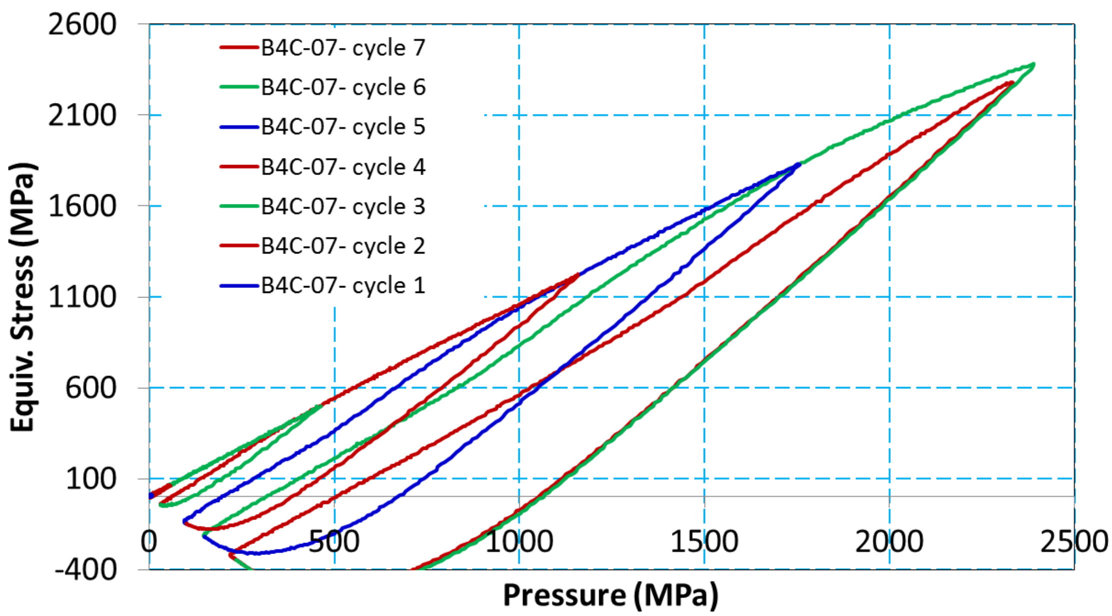
B4C-07

Weight: 0.399g

Initial Length: 0.450in

Post Length: 0.265in





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Sidney Chocron	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

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Southwest Research Institute P.O.Drawer 28510 San Antonio TX 78228-0510	SWRI-18-22296

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	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

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13. SUPPLEMENTARY NOTES

Johns Hopkins University worked with SWRI on this project.

14. ABSTRACT

The purpose of this investigation was to perform confined compression tests on a boron carbide (B4C) powder similar to that used to fabricate the baseline tiles used in the MEDE program. The tests were designed to measure the axial stress, hoop strains, confinement and hydrostatic pressures, and equivalent stresses within the powder material during compression.

Similar tests were documented in SwRI Report 18.06188 (Ref. [1]), where the details of the procedure are reported. The provided data could be used to fit a material constitutive model such as Drucker-Prager in order to simulate the B4C powder within a hydrocode or other finite element program.

15. SUBJECT TERMS

Boron carbide powder, physical characteristics, physical properties

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Sidney Chocron, Ph.D.
U	U	U	U	24	**19b. TELEPHONE NUMBER** *(Include area code)* (210) 522-3698