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***Characterization of Confined Strength
of Intact and Damaged B₄C and SiC***

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14. ABSTRACT This report summarizes the characterization work performed on intact and predamaged boron carbide and silicon carbide tested in compression. Confined compression testing was conducted using a pressure vessel or using a thick steel confining sleeve. Optical and stereomicroscopy were used to evaluate, document, and provide insights to the damage morphology. The effect of pressure (up to 2 GPa hydrostatic pressure) on the strength of the two materials is quantified. The failure curves obtained are presented and written as Drucker-Prager and Mohr-Coulomb failure criteria. Results are discussed and compared to the literature. It is shown that data obtained with very different techniques (confined compression, plate impact and divergent plate impact) are in reasonably good agreement.				
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1.0 Introduction

This report summarizes the characterization work performed on intact and predamaged boron carbide and silicon carbide tested in compression under confinement in a pressure vessel or using a thick steel confining sleeve. From the literature review, it can be argued that the strength of these ceramics, in an intact state, depends mainly on: 1) surface defects, 2) hydrostatic pressure, and 3) strain rate. It is also known that internal defects can affect the strength, though processing techniques to eliminate internal defects are beyond the scope of this report.

As early as in the 1940s, Bridgman [1] tested alumina and glass at high confinement pressures showing a remarkable increase in strength. Based on Griffith's theory, he concluded that surface defects on ceramics are less important at high pressures. Their strength approaches the theoretical value because "surface action that would take place at fracture is not energy-releasing" (pg. 127 of his book). The effect of confinement pressure on brittle materials has, since then, been widely studied. Wilkins et al. [2] tested boron carbide and other ceramics under confinement, providing strength data for both intact and damaged material; their results will be compared to the current work. Heard and Cline [3] showed brittle to ductile transition in BeO and AlN ceramics under pressure but were not able to get to the transition point for alumina.

Johnson et al. [4] (see also [5]) tested silicon carbide and pyroceram at low and high strain rates finding that at atmospheric pressure that the strength of both ceramics increased significantly at high strain rates. They also showed that strain-rate-strengthening effects decreased with confinement. This observation was rationalized by Lankford et al. [6] in a very interesting manner. Lankford stated that, for alumina, tests as different as nanoindentation, split Hopkinson bar and plate-impact gave similar strengths if the ceramic was sufficiently confined. His argument was based on crack dynamics and the fact that plastic flow started to be important at high pressures (or plate impact rates) for ceramics. His perspective is summarized in [7].

Other relevant work by Chen and Ravichandran [8] and [9] shows strain-rate sensitivity for aluminum nitride under moderate confinement (< 250 MPa) by confining the specimen with a thin metallic sleeve. Ahrens et al. [10] (see also Chen and Ravichandran [11]) tested a glass ceramic, Macor, under low confinement pressures at quasistatic and Hopkinson bar rates. They observed strain rate dependence and were able to establish a rationale, based on fracture mechanics, for the use of a Mohr-Coulomb failure criterion at these low pressures, while they expected to see plastic flow at high pressures. The thin sleeve technique has been used extensively to test both intact and damaged ceramics, see for example Luo et al. [12] where SiC-N was tested with a double pulse Hopkinson bar technique. A summary of the different techniques is provided in a review paper by Chen et al. [13]. Paliwal et al. [14] explored a different (lateral) confinement technique for an AlON prismatic specimen, but only scoping studies were reported.

High pressures are difficult to attain in pressure vessels due to leakage at seals. An option to obtain larger confinement pressures is to use a thick steel sleeve that is honed to tightly fit the specimen. Walker et al. [15], using an autofrettaged confinement, achieved pressures close to 1 GPa. Ma and Ravi-Chandar [16] demonstrated the thick sleeve technique with an aluminum specimen. Chocron et al. [17] recently used the technique to characterize intact and confined borosilicate glass attaining a confinement pressure of ~ 1 GPa. This technique will also be used in the work presented here.

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For even higher pressures, indentation or plate-impact techniques need to be used. See Holmquist and Wereszczak [18] for a comparison of constants obtained for SiC using both techniques. Of particular interest for this work are the plate-impact results obtained by various authors since they provide an independent measurement of the strength of the ceramic with a very different technique than compression under confinement. These two techniques are naturally complementary. If correctly interpreted, they should overlap at the low end of the plate-impact pressures. The data that will be used in this report come from various papers published by Johnson and Holmquist for boron carbide ([19], [20]) and for silicon carbide ([21], [22]). Recent work on both materials by Zaretsky et al. [23] and by Paris et al. [24] has opened a whole new possibility of mapping the equivalent stress vs. pressure plane and will also be used in this report.

As described in this introduction, based on a comprehensive review of the literature, strain rate effects and surface defects seem to be of second-order importance with respect to the strength. Hence, the focus of this work is on the effect of pressure on the strength of silicon carbide and boron carbide. The techniques used for characterization are described briefly. Then the failure curves obtained for both materials are presented. Finally the results are discussed and compared to the literature previously mentioned.

2.0 Materials and Methods

2.1 Materials

Boron carbide (B_4C) and silicon carbide (SiC-N) ceramics were characterized in this program. Similar characterization of SiC-N was performed for a 2004 program funded by ARL [25]. However, subsequent evaluations of Borofloat [26] and Starphire [27] glasses resulted in several advances in test methodology and analysis. These improvements have been applied in this work to evaluate the ceramic materials of interest.

Both materials were obtained from BAE Systems (Vista, CA) and were produced using a pressure assisted diffusion (PAD) process. The elastic mechanical properties and Knoop microhardness for the B_4C and SiC-N materials were provided by BAE. These are summarized in Table 1. Property differences between B_4C and SiC-N are apparent upon comparison of the first two data columns. B_4C is harder than SiC-N with lower density and Poisson's ratio. The longitudinal and shear wave velocities for B_4C are slightly higher than measured for the SiC-N material. Table 1 also includes data for SiC-N materials used for previous test programs([25], [28]), as well as typical SiC-N properties reported on the BAE website. Comparison of the SiC-N properties shows good consistency among the three datasets.

Table 1: Mechanical Properties for B_4C and SiC-N

	B_4C	SiC-N	SiC-N 2004 Program [25]	Failure Wave Program [28]	SiC-N Typical [29]
Bulk Density, ρ (g/cc)	2.518	3.228	3.21	3.21	3.20
Knoop Hardness**(kg/mm ²)	2615 +/- 12	2354 +/- 15	2389 +/- 55	2371 +/- 41	2400
Longitudinal Velocity, c_L (km/s)	13.70	12.29	12.30	12.26	12.00*
Shear Wave Velocity, c_S (km/s)	8.73	7.68	7.78	7.78	7.91*
Poisson's Ratio, ν	0.158	0.178	0.173	0.163	0.16
Young's Modulus, E (GPa)	443	449	450.6	452.1	460
Shear Modulus, G (GPa)	191	191	192.1	194.4	200*

* Calculated value

** The Knoop hardness test is a micro-indentation method that employs a diamond indenter to apply a load to the test sample. The dimensions of the resulting indentation are measured; the Knoop hardness number is the ratio of the applied load to the area of the indentation.

2.2 Specimen Preparation

Cylindrical specimens were utilized for all confined compression tests on the B_4C and SiC-N ceramics. Specimens were machined by BAE Systems according to SwRI drawings. BAE also machined cylindrical anvils of SiC-N used to load the B_4C and SiC-N specimens during

testing. Both intact and predamaged specimens were tested in compression inside a hydraulic pressure vessel or steel confining sleeve. The intact ceramic specimens measured 6.25 mm in diameter and 12.7 mm long.

Specimens were predamaged prior to conducting compression tests under pressure to lower the strength of the ceramic, and to initiate a damage state. Predamaged specimens were obtained by exposing intact specimens to a thermal cycle. Specimens were exposed individually in a resistance furnace for one hour at 750°C, followed by an ice water quench. The B₄C specimens were exposed to two thermal cycles; three thermal cycles were used to predamage the SiC-N specimens.

Several specimens were sectioned and polished to evaluate the extent of damage and determine the consistency of the damage pattern at several locations along the specimen length. The predamage condition of a representative SiC-N specimen, following three thermal cycles at 750°C is shown in Figure 1. The transverse-sections shown in the figure are for the specimen end, and two other sections located 3-mm and 9-mm away from the specimen end. The SiC-N specimens exhibited several non-contiguous cracks due to thermal cycling. The specimens could be handled readily without loss of structural integrity.

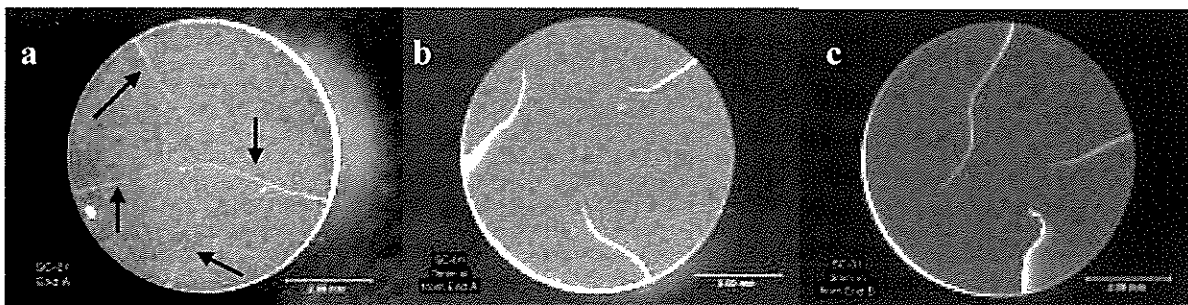


Figure 1. Polished cross sections of a predamaged SiC-N specimen following the thermal shock procedure. (a) Specimen end; cracks are marked by the arrows, (b) Same specimen, 3 mm from the location shown in (a), (c) Same specimen, 9 mm from the location shown in (a).

The B₄C specimens were exposed to two thermal cycles to predamage the specimens. Application of the same thermal shock treatment as for the SiC-N specimens (i.e., three 1-h thermal cycles at 750°C with each cycle followed by an ice water quench) resulted in extensive cracking of the B₄C specimens. Numerous contiguous cracks were observed, as shown in Figure 2(a). Upon sectioning this specimen to evaluate the consistency of the crack pattern along the specimen length, it disintegrated into several pieces. Thus, three thermal cycles proved too severe for the B₄C specimens. The crack pattern for B₄C following two thermal cycles is shown in Figure 2(b). A contiguous crack pattern resulted, but specimen integrity was maintained (i.e., it could be handled without disintegrating into pieces). A single thermal cycle was also evaluated for another B₄C specimen, Figure 2(c); cracking was not observed under microscopic evaluation of the specimen. Based on these findings, a two-cycle thermal shock procedure was employed to predamage the B₄C specimens.

Dimensions of the predamaged B₄C and SiC-N specimens were measured with a caliper, and were unchanged from the intact specimens.

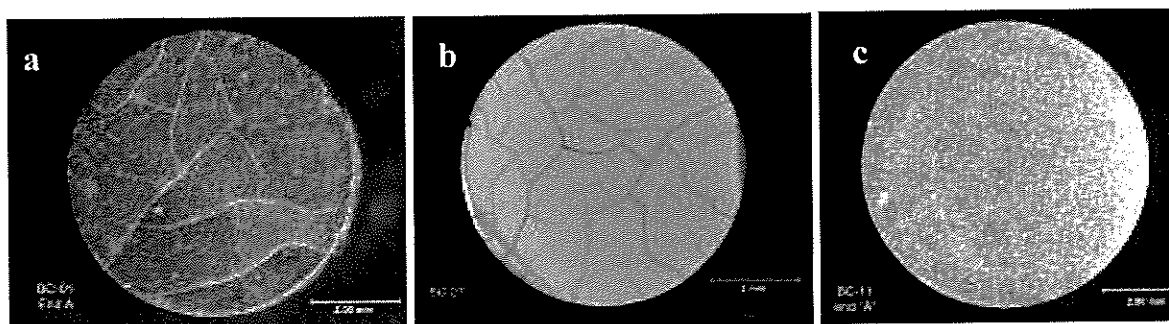


Figure 2. Damage pattern for three different B₄C specimens following 1h thermal cycles at 750°C, with each cycle followed by an ice water quench. (a) Three thermal cycles, (b) Two thermal cycles; (c) One thermal cycle.

2.3 Overview of Compression under Confinement

Confined compression tests were conducted on the two ceramic materials of interest. Tests were conducted at low strain rates ($\sim 10^{-4} \text{ s}^{-1}$) on both intact and predamaged specimens. Several unconfined compression tests were also performed on intact B₄C specimens for comparison with the confined test results. All quasistatic tests were performed with an MTS servohydraulic machine. Several high strain rate ($\sim 10^3 \text{ s}^{-1}$) compression tests were also conducted on intact B₄C under hydraulic confinement. These tests utilized a Hopkinson (Kolsky) bar setup with 1.27-cm diameter maraging steel bars. The test matrix for the B₄C and SiC-N ceramics is outlined in Table 2.

Table 2. Testing Summary

Material	Condition	Confinement Method	Confinement Pressure (MPa)	Approximate Strain Rate (s^{-1})
B ₄ C	Intact	None	-	10^{-4}
	Intact	Hydraulic	50,100,200	10^{-4}
	Predamaged	Hydraulic	50,150,350,500	10^{-4}
	Predamaged	Sleeve	1000*	$10^{-4}, 10^3$
SiC	Predamaged	Hydraulic	50,150,350,500	10^{-4}
	Predamaged	Sleeve	1000*	10^{-4}

*The confining pressure for the sleeve tests varies with loading. The maximum pressure that can be achieved for these tests is approximately 1 GPa.

Two different confinement methods were employed for the tests: (i) mechanical confinement, using a high-strength steel confining sleeve, and (ii) hydraulic confinement (i.e., triaxial compression). For the mechanical confinement tests on predamaged specimens, loading of the specimen was performed using a load/unload/reload sequence at successively increasing loads. This “failed” the material *in-situ*, creating comminuted ceramic. The maximum radial pressure achieved with the confinement sleeve tests was approximately 1 GPa. Peak radial pressures approaching 500 MPa were obtained with the hydraulic confinement technique. The test methods are briefly described in the following sections.

Triaxial compression and confining sleeve techniques are complementary. Confining pressures for triaxial compression tests are lower than for the confining sleeve technique. The two techniques overlap at confining pressures of 300 to 400 MPa. The higher pressures achieved in the confined sleeve tests allow comparison of the test results with flyer-plate impact data in the literature. Flyer-plate impact experiments interrogate material response at very high strain rates, and thus, the comparison can provide insight on strain-rate effects.

2.4 Triaxial Compression Technique

The triaxial compression test is a “classic” test used to characterize pressure-dependent materials like sand or concrete (e.g., see Ref. [30]). Test results obtained using this technique allow a straightforward determination of Drucker-Prager [31] or Mohr-Coulomb [32] plasticity models. A specimen is placed inside a thick-wall steel pressure vessel (the pressure “bomb”). The pressure bomb is placed in an MTS machine. A steel piston runs from the loading platen of the MTS machine to the specimen through an alumina-loading anvil. A hydraulic fluid, controlled by a pump, is used to load the specimen at different constant fluid pressures. The axial load is applied by the MTS machine.

The set-up is illustrated in Figure 3. The intact or predamaged specimens are introduced in a pressure vessel where they are loaded by a piston through two alumina anvils. The specimen is placed inside a pliable plastic (shrink tubing) sleeve to protect the specimen from the hydraulic fluid. A very thin (2-mil-thick) brass element is wrapped around the Teflon sleeve to help preclude easy tearing of the Teflon sleeve by fragments formed from specimen failure during loading. The load is measured by a load cell placed inside the pressure vessel and wired directly to provide the equivalent stress acting on the specimen. For this simple load configuration with cylindrical symmetry, the equivalent stress is:

$$\sigma_{eq} = |\sigma_z - \sigma_r| = \tilde{\sigma}_z - \tilde{\sigma}_r \quad (1)$$

where σ_z is the axial load applied through the piston and σ_r is the fluid pressure ($\sigma < 0$ in compression, $\tilde{\sigma} > 0$ in compression). The hydrostatic pressure on the specimen is then given by:

$$P = \frac{1}{3}(2\tilde{\sigma}_r + \tilde{\sigma}_z) \quad (2)$$

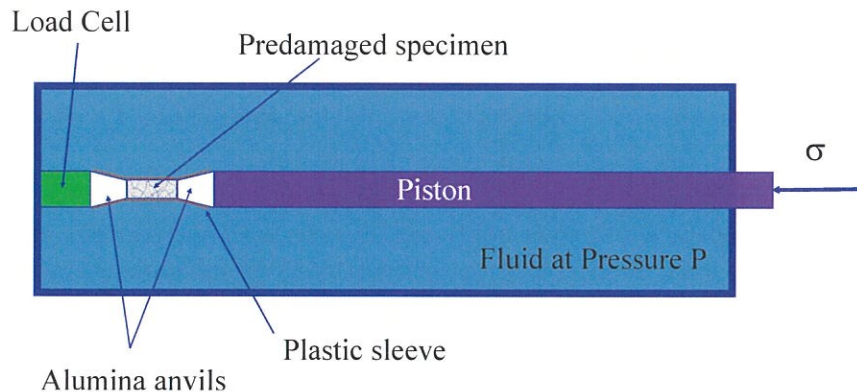


Figure 3. Hydraulic bomb experimental set-up.

Figure 4 shows the specimen, the anvils and the load cell before being placed inside the pressure vessel. The maximum pressure that can be obtained in the vessel is 500 MPa due to limitations of the feed-through seals. Tests were performed at fluid pressures of 50, 150, 350 and 500 MPa. During a preload phase, the specimen axial stress and the fluid pressure are kept equal (hydrostatic stress in the specimen) to avoid premature failure. When the desired confinement pressure is attained, the test is initiated by increasing the axial load for compression, or slowly decreasing the axial load for tension, while leaving the fluid pressure constant. The axial strain in the specimen is measured during the test with a calibrated clip gage.

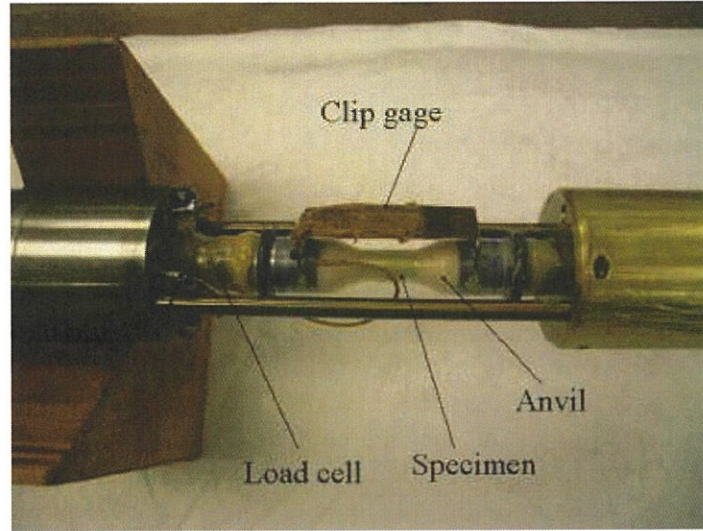


Figure 4. Specimen placement prior to insertion into the pressure vessel.

2.5 Specimen Confinement in a Sleeve

The second testing technique uses a high-strength steel sleeve to confine the specimen. The specimen is inserted into a Vascomax C350 steel sleeve that is honed to fit the specimen, see Figure 5. Vascomax C350 is a maraging steel with an approximate yield strength of 2.4 GPa. The sleeve outer diameter is 12.70 mm and the thickness 3.17 mm. An axial compressive stress is applied to the specimen with an MTS servohydraulic machine by means of two SiC-N platens, located on either end of the specimen.

The variables recorded during the test are the axial stress in the specimen, measured by a load cell in the MTS machine; axial strain in the specimen, measured by a clip gage placed on the top and bottom platens; and hoop strain in the sleeve, measured by two strain gages on the sleeve located 180 degrees apart. Similar to the hydraulic bomb, it is convenient to consider the stress positive in compression. The confinement (radial) stress increases as the axial load is applied. The radial stress is related to the hoop strain ϵ_θ , measured on the outer diameter of the steel sleeve by:

$$\tilde{\sigma}_r = \frac{E_{sl}}{2} \frac{b^2 - a^2}{a^2} \epsilon_\theta \quad (3)$$

where E_{sl} is the elastic (Young's) modulus of the sleeve; a and b are the inner and outer radii of the sleeve, respectively. This analysis assumes that the sleeve remains elastic (which is the

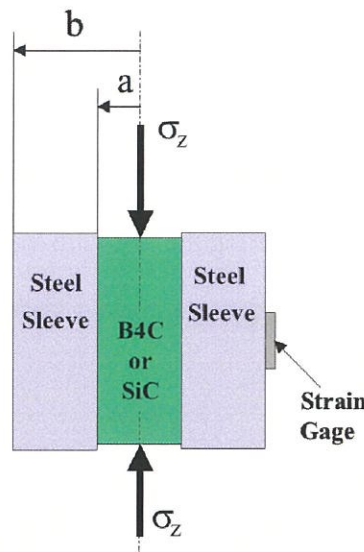


Figure 5. Confined sleeve assembly. The strain gage is used to measure hoop strain in the sleeve.

primary reason for using a Vascomax steel sleeve). The hydrostatic pressure is given by Eqn. (2). The hoop strain is used to infer the “internal pressure” of the sleeve, i.e., the radial stress that the specimen exerts on the sleeve, which is also the confinement pressure of the specimen. It is important to point out that the confinement pressure increases during the test. Extensive discussion of interpretation and the results of this technique can be found in [26] (see also [27], [17], [33]). Acoustic emission was independently recorded to assist in determination of damage “events” that occur within the specimen during the test.

The sleeve technique can also be applied at high strain rate using the split-Hopkinson pressure bar. In this case, the sleeved specimen is placed between the incident and output bar of the split-Hopkinson bar. The steel confining sleeve, with the hoop strain gage in place, is shown in Figure 6. Alumina and silicon carbide anvils are used to transfer the load from the bars to the specimen. The SiC-N anvils are situated adjacent to the specimen ends; the alumina anvils are located between the SiC-N anvils and the bar.

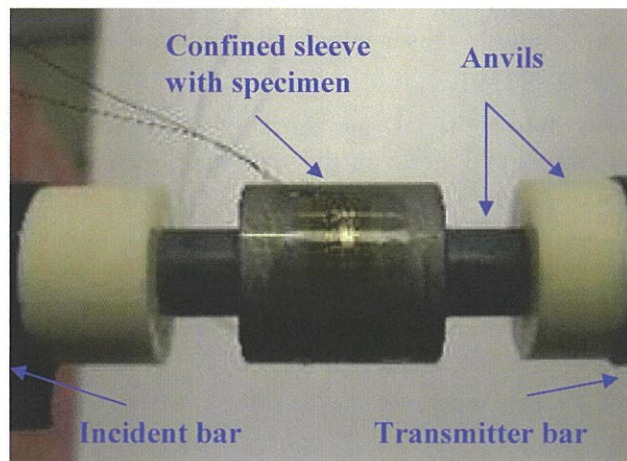


Figure 6. Confined sleeve test assembly, situated in the split-Hopkinson bar, for high strain rate compression tests.

3.0 Results on Boron Carbide

3.1 Introduction

The interpretation of the triaxial compression tests is straightforward. The axial stress is directly derived from the load measured with the load cell ($\tilde{\sigma}_z = \sigma_{eq} + \tilde{\sigma}_r$) and the hydrostatic pressure on the specimen is inferred from $P = (\tilde{\sigma}_z + 2\tilde{\sigma}_r)/3$.

The primary objective of this work is to evaluate how the failure stress of intact and damaged boron carbide varies with pressure. Two well known pressure-dependent constitutive models—the Drucker-Prager (DP) and Mohr-Coulomb (MC) models—will be used to interpret the data. For the DP model, the failure stress of the different specimens is plotted in a σ_{eq} versus P graph. For the MC model, following Desai's [30] recommendation, the failure points are plotted on a $(\sigma_1 - \sigma_3)/2$ vs. $(\sigma_1 + \sigma_3)/2$ graph, where σ_1 and σ_3 are the maximum and minimum principal stress, respectively.

Table 3 lists all the tests performed on boron carbide. Triaxial compression was performed on 5 intact and 8 predamaged specimens. Two specimens (17 and 18) were tested under tension; i.e., after reaching the hydrostatic state, the axial load was gently relaxed until failure.

Table 3. Boron Carbide – Test Summary.

Specimen	Test type	Confinement Pressure (MPa)	Specimen initial condition	Specimen	Test type	Confinement Pressure (MPa)	Specimen initial condition
BC-02	Triaxial	50	Intact	BC-19	Sleeve	n/a	Predamaged
BC-03	Triaxial	50	Intact	BC-20	Sleeve	n/a	Predamaged
BC-04	Triaxial	100	Intact	BC-21	Sleeve	n/a	Predamaged
BC-05	Triaxial	100	Intact	BC-22	Sleeve	n/a	Predamaged
BC-06	Triaxial	200	Intact	BC-23	Sleeve	n/a	Predamaged
BC-07	Triaxial	50	Predamaged	BC-24	Sleeve	n/a	Predamaged
BC-08	Triaxial	50	Predamaged	BC-25	Sleeve	n/a	Predamaged
BC-09	Triaxial	150	Predamaged	BC-26	Sleeve	n/a	Predamaged
BC-12	Triaxial	350	Predamaged	BC-28	Sleeve	n/a	Predamaged
BC-13	Triaxial	500	Predamaged	BC-29	Unconfined	0	Intact
BC-14	Triaxial	500	Predamaged	BC-30	Unconfined	0	Intact
BC-15	Triaxial	150	Predamaged	BC-31	Unconfined	0	Intact
BC-16	Triaxial	350	Predamaged	BC-32	Sleeve	n/a	Predamaged
BC-17	Triax.-tension	350	Predamaged	BC-33	Sleeve	n/a	Predamaged
BC-18	Triax.-tension	500	Predamaged				

*All the tests were quasistatic except for BC-28, 32 and 33 which were performed in the Hopkinson bar ($\sim 10^3 \text{ s}^{-1}$).

3.2 Triaxial Compression Tests of Intact and Predamaged Specimens

The load curves shown in Figure 7 are for intact and predamaged specimens, tested inside the pressure vessel. The response of the intact specimens is linear up to failure, while predamaged specimens deviated slightly from linearity right before failure. Intact specimens were tested at 50, 100 and 200 MPa. Specimen BC-06, an intact specimen tested under 200 MPa confinement (not shown), did not fail before reaching the maximum capacity of the MTS machine; therefore, only a lower limit for the strength at this pressure was obtained (5.2 GPa).

There is a qualitative difference between failure of intact and predamaged specimens. When intact specimens fail, the supporting anvil also fails leading to an immediate and complete unload, denoted by the downward vertical arrow in Figure 7. Predamaged specimens, after reaching a maximum stress, suddenly decrease their load carrying capability but do not lose it completely (i.e., they have a “residual” strength). The elapsed time between maximum loads and residual strength was ~ 0.25 seconds for the predamaged specimens. Each data point in the figure represents a 5 second interval. The actual acquisition rate was 100 times faster, but the number of points was reduced for clarity.

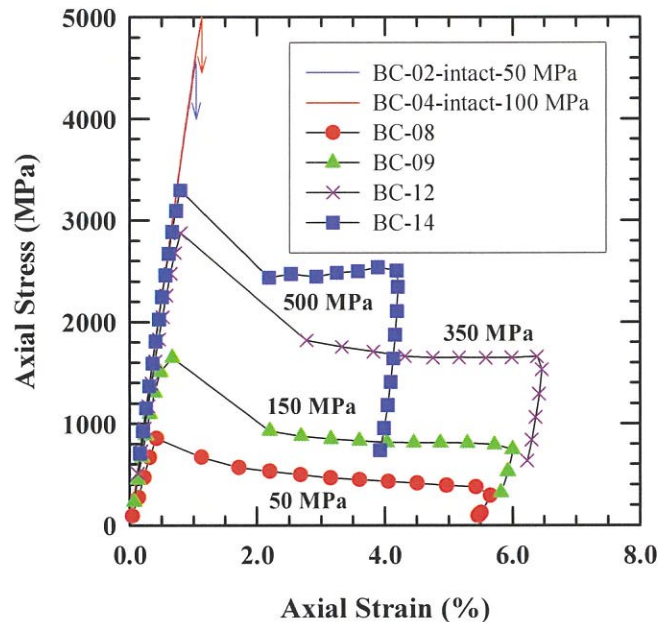


Figure 7. Two intact specimens (BC-02 and BC-04) and four predamaged B₄C specimens tested in the bomb at different nominal confinement pressures.

The residual load is due to friction between the two planes of a diagonal fault that forms in the specimen at an average angle of 30 degrees, measured from the axial direction (60 degrees from the direction of confinement pressure). It is interesting to note that both Bridgman [1] and Wilkins [2] observed a similar slip plane when they tested *intact* glass and *intact* boron carbide, respectively. The angle of the slip plane reported by Wilkins is 20 to 45 degrees from the axial direction. The angles found for the present work ranged from 23 to 37 degrees. Pictures of the angle are provided in the post-test evaluation section (Figure 19).

The triaxial compression tests performed in the pressure vessel are summarized in Figure 8. The red squares represent the tests performed on intact specimens. All the intact unconfined points lie on the dashed line with a slope of 3 since, if the specimen is unconfined, the equivalent stress equals the axial stress, which is three times the pressure. The strength ranges from 2.6 to 4.2 GPa, so the scatter in failure stress is very large, a common finding for brittle materials.

The scatter reduces drastically once the specimen is under confining pressure, as shown by the open blue triangles. This is consistent with Bridgman's [1] observation that surface finish or cracks have less influence on the strength when the material is under confinement. The last data point for intact specimens under confinement has an arrow indicating that this specimen (BC-06)

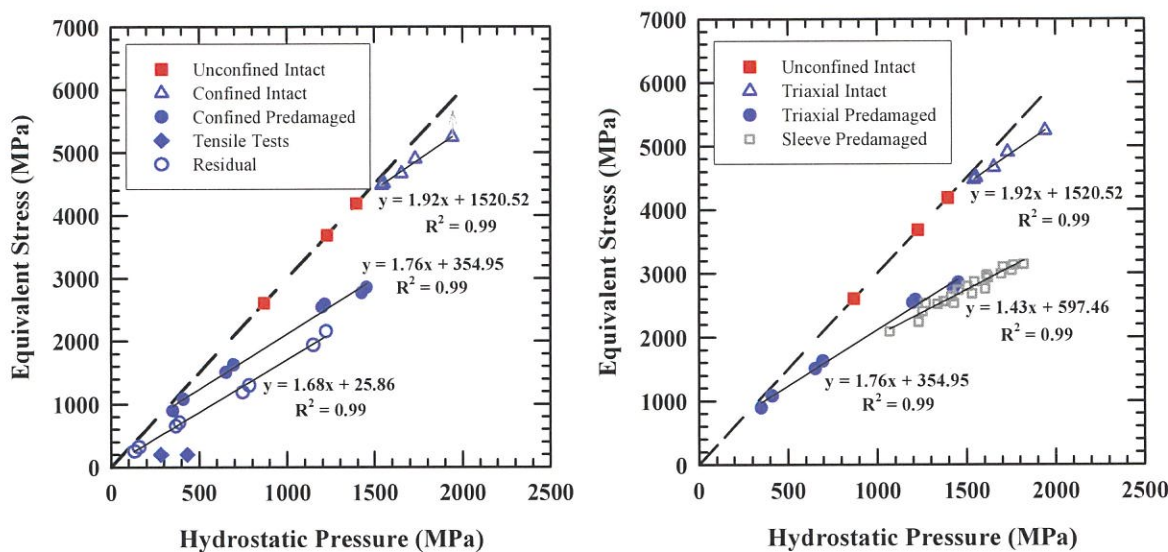


Figure 8. Strength of intact and predamaged boron carbide specimens tested under different confinement pressures: a) triaxial compression and tension, b) Sleeve tests are added.

did not fail so it is only a minimum strength at a confinement pressure of 200 MPa. This point was nevertheless used in the linear regression shown in the plot since, presumably, it was close to failure. If this point is not used in the linear regression the slope changes from 1.92 to 2.11 and the correlation coefficient R^2 from 0.99 to 0.97.

The strength of predamaged specimens is shown with solid blue circles in Figure 8. For the range of pressures tested the strength is linear with hydrostatic pressure with a slope similar to the confined intact specimens. These data will be compared later to the data that Wilkins obtained for fractured boron carbide, showing a striking similarity.

Residual strength is also reported in Figure 8 as open blue circles. As seen in Figure 7, after failure the strength decreases gradually until leveling off (actually not all the tests level off). The mechanism responsible for the gradual decrease and stabilization of the strength is speculated to be the following: when failure occurs, a sudden fault appears, giving rise to two new surfaces. These new surfaces are probably quite rough so the friction coefficient between them is large. Once the motion between the two surfaces start, frictional flow progressively smooths the surfaces decreasing the stress required to have relative motion between them. Eventually, when the surfaces are sufficiently smooth, the stress required for the two surfaces to slide is approximately a constant. For this reason, the stress shown in Figure 8 was chosen to be the plateau stress (or the minimum if there was no plateau) seen on the axial stress vs. strain curves. It is remarkable to see that the residual stress points lie on a straight line, of slope ~ 1.7 with a correlation coefficient of 0.99.

Figure 8 also reports the results of two triaxial tests, BC-17 and 18, in tension (solid blue diamonds) under a confinement pressure of 350 MPa and 500 MPa respectively. Failure of these specimens is very different from failure under triaxial compression. There were two failure planes perpendicular to the axis of the cylinder (see Figure 21 in post-test evaluation section) similar to what was seen also by Bridgman [1] and by Wilkins [2], although the failure surfaces were rough. Figure 9 displays the response curves obtained for the two triaxial tension specimens. Failure of these specimens is not obvious when looking at the axial stress vs. axial strain response.

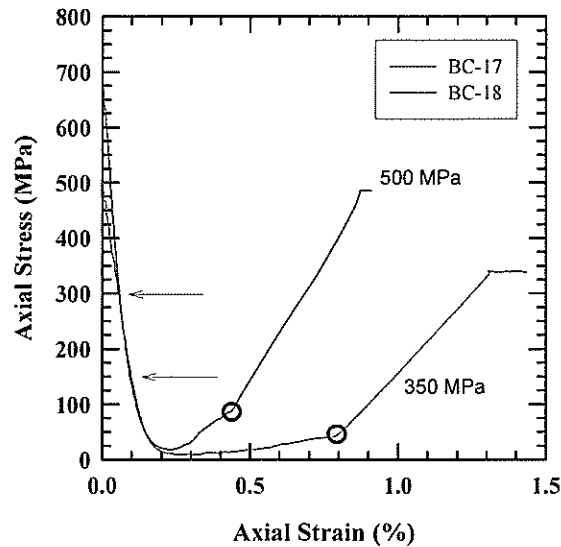


Figure 9. Tests performed in triaxial tension.

As mentioned previously, these specimens were loaded hydrostatically (this load is not shown in Figure 9) to avoid premature failure of the specimen. Once the hydrostatic state was achieved, the axial load was increased slightly (to 500 MPa for the specimen under a confinement of 350 MPa and to 700 MPa for the one at 500 MPa) before starting the test. Then the axial load was gently released, see Figure 9. From the figure it is not obvious when failure occurs since there is no sharp decrease in load before the axial stress reaches zero value (i.e. the piston and specimen start losing contact or the specimen splits). For the data shown in Figure 9, it was assumed that failure occurred when the axial stress vs. axial strain deviate from linearity, which happened for both specimens at an equivalent stress of approximately 200 MPa (axial stress of 150 MPa for BC-17, red arrow, and 300 MPa for BC-18, blue arrow). This is in agreement with Wilkins' [2] observation that under triaxial tension the failure stress does not seem to depend on the confinement pressure. Nevertheless caution is advised with these data and interpretation since a non-linearity was also observed for a similar test of SiC in tension that did not fail (see SiC section).

Note that the data in Figure 9 shows that the unloading response remains smooth until almost complete unload is reached. Then the axial stress increases and returns quickly (at the kinks highlighted by the circles) to the confinement pressure. This effect can be explained as follows: once the specimen fails, small cracks (perpendicular to the axis of the cylinder) form and a non-linear more complex interaction among the specimen fragments, the brass foil, and the plastic tube that surrounds the brass, is initiated. Once the axial stress vanishes, the ceramic fragments should start separating and the fluid that surrounds the specimen will try to fill the voids created increasing the internal load on the fragmented specimen. At some point the plastic and brass sleeves implode and the axial load returns to the initial confinement pressure.

3.3 Confined Sleeve Experiments

A total of 11 predamaged specimens were tested in the sleeve. No tests were performed on intact specimens because the strength of intact boron carbide at confinement pressures over 200 MPa is above the limit of the MTS machine used. For the sleeve tests, the equivalent stress is again given by $\sigma_{eq} = \tilde{\sigma}_z - \tilde{\sigma}_r$, but now the confinement pressure $\tilde{\sigma}_r$ increases during the test,

see Eqn. (3). If the sleeve deforms elastically and uniformly, $\tilde{\sigma}_r$ can be approximately calculated from the elastic solution (see for example Ref. [34]):

Figure 10 shows a typical test of predamaged boron carbide (specimen BC-20) inside the Vascomax sleeve. Seven consecutive load/unload cycles, with progressive increase on the maximum load applied, were performed on this specimen. On the axial strain vs. hoop strain plot, sudden jumps are apparent during the loading process. These jumps are ascribed to fault planes forming and slipping during loading [17] and, consequently, are considered a characteristic of the material for the corresponding confinement pressure.

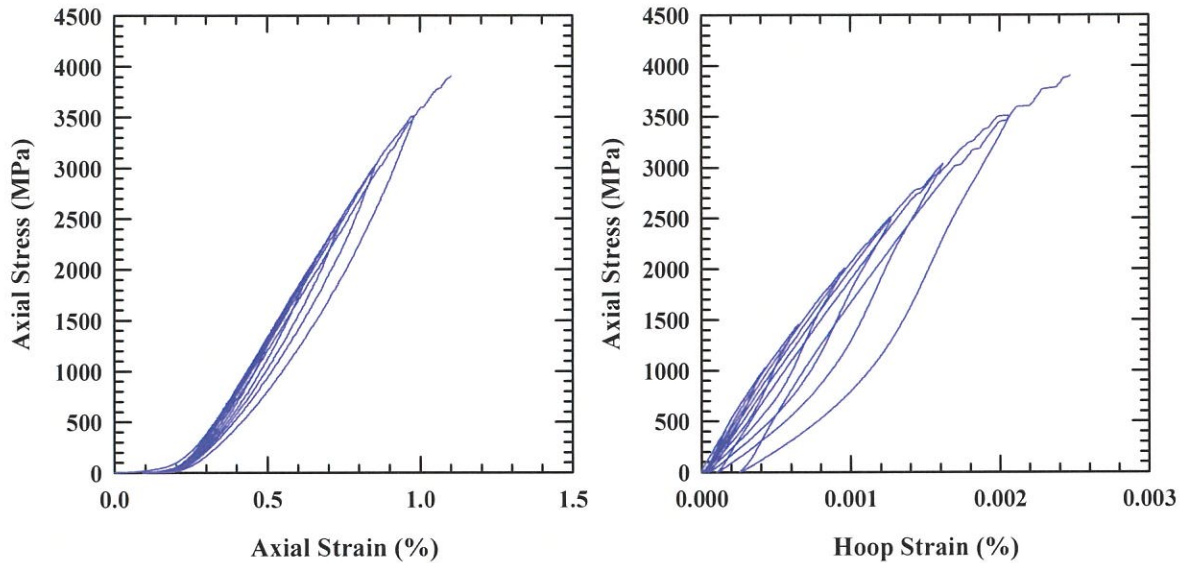


Figure 10. Curves obtained for specimen BC-20, a predamaged specimen inside a confinement sleeve: a) axial stress vs. axial strain, b) axial stress vs. hoop strain.

The jumps for all the tests were collected and represented in the equivalent stress vs. pressure plane as shown in Figure 8(b) (open grey rectangles). Some of the data lie slightly below the data obtained in the triaxial compression test, but for a pressure of 1.5 GPa, the data overlap. A linear regression to the sleeve data provides a slope of approximately 1.4. The sleeve technique provides data at pressures somewhat larger than for the pressure vessel (1.9 GPa vs. 1.5 GPa) so the Drucker-Prager model can be extended to slightly higher pressure. In the next subsection, more insight on these data will be provided.

The Hopkinson bar tests performed on B₄C were, unfortunately, inconclusive. For the three tests performed, only one jump could be clearly identified at a pressure of 1.1 GPa with an equivalent stress of 2.3 GPa. This point is consistent with the data in Figure 8(b). A more intense research effort is required to examine high strain rate response of these ceramic materials.

3.4 Discussion of Boron Carbide Results

The triaxial compression and sleeve tests are compared with available data in the literature. Figure 11 shows all the data collected during this effort together with data from Wilkins et al. [2] and Paris et al. [24].

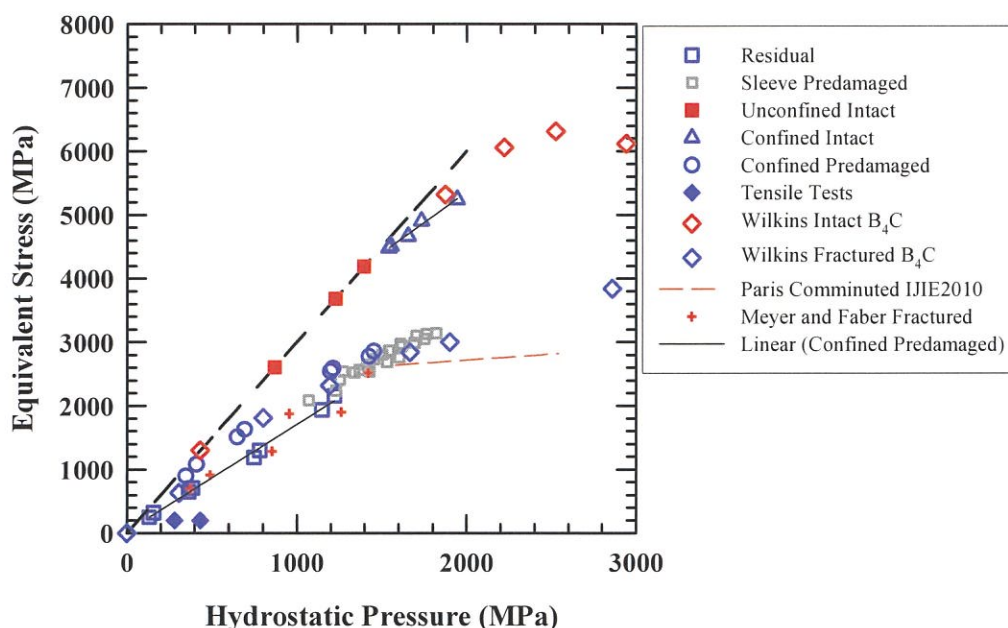


Figure 11. Boron carbide data are compared to literature results.

The first striking feature is the low strength (1.3 GPa) of the unconfined boron carbide (hot pressed) tested by Wilkins, represented by the open red diamond on the slope 3 line. The strength measured in this project was between 2.6 and 4.2 GPa so, although the scatter is very large, the current B_4C ceramic is clearly stronger. This is not necessarily surprising since a difference might be expected between specimens manufactured 40 years apart. But Figure 11 also shows that under confinement the intact specimens tested by Wilkins (open red diamonds for $P > 1500$ MPa) have a strength similar to the ones tested in this effort. According to Bridgman [1], it is expected that under compression, strength dependence on surface conditions should become negligible. So it is possible that the difference between Wilkins' and SwRI's specimens is only the surface conditions. This implies that the B_4C tested at SwRI is not that different from the one tested by Wilkins 40 years ago.

Wilkins' data for fractured B_4C (open blue diamonds) seem to confirm that both ceramics are similar. The data represented as open red diamonds in Figure 11 were recorded by Wilkins during the confined intact tests. His specimens did not fail in a catastrophic way, unlike the ones tested at SwRI. After failure, Wilkins' specimens could still carry load due to frictional sliding between the broken fragments, which is what was observed for SwRI's *predamaged* specimens. The fact that the strength after fracture measured by Wilkins overlaps with the strength measured by SwRI (blue open circles and gray small rectangles) for predamaged specimens probably indicates that Wilkins' fractured specimens were in a very similar condition to SwRI's predamaged specimens.

Figure 11 also shows a dashed line with failed boron carbide data recently obtained by Paris et al [24]. These were obtained with a technique called divergent impact which is similar to the plate-impact but allows excursions to stress states that the conventional plate impact technique cannot achieve. Paris et al., obtained these results by matching the results of an assumed failure model to signals recorded during the test. The fact that the strength of the failed material measured with the divergent impact technique is close to the strength obtained with quasistatic techniques implies that strain rate does not seem to be a factor under confinement pressure.

Lankford [7] already mentioned this possibility, which he interpreted to be the consequence of crack dynamics.

Meyer and Faber [35] data are shown as red crosses in Figure 11. They fragmented boron carbide with a plate impact technique and then tested the failed material in a confinement ring similar to the sleeve test performed in this project. It is interesting that their data overlap the residual strength of the boron carbide tested in the pressure vessel since, in principle, comminution of the material has been obtained by two very different techniques. Probably the initial size distribution of the fragments is very different, but plate impact and a thermal shock exposure followed by triaxial testing provide similar strength versus pressure response. A possible explanation is that the particles formed in the fault planes need to have a characteristic size (that depends on the pressure) to start sliding. This would imply that the initial fragment size is not relevant and that during the test the particles are broken more and more before and during sliding. At some point the particles are fine enough that no subsequent failure happens and the stress level reaches a plateau.

High-pressure data obtained with plate impact are also shown in Figure 12. Red hollow squares are intact B_4C data from Paris and the blue star is an average Hugoniot elastic limit reported by Holmquist and Johnson [20] from a paper by Vogler et al [36]. The dashed blue line is an envelope of the data. For intact B_4C , given the data available, it is not possible to argue in favor of strain rate dependence or independence since data do not overlap. In fact the last point obtained by Wilkins (at a pressure of approx. 4.2 GPa) might mean that at low strain rates that the strength is smaller. Since it is only one data point it is not possible to be conclusive. Additionally, the HEL reported by Vogler lies below the Paris data, which provides further uncertainty in any strain-rate effect.

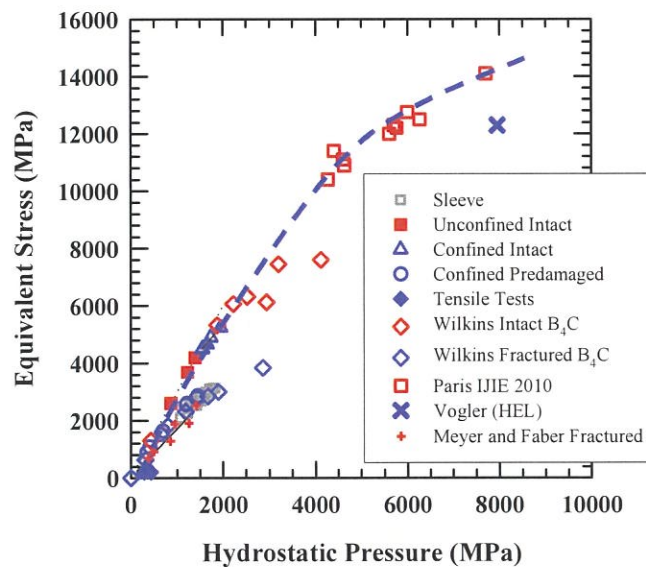


Figure 12. Comparison with higher pressure plate impact data.

3.5 Conclusions for Damaged Boron Carbide

- Under confinement, Wilkins' data and the current work provide essentially the same σ_{eq} vs. P response. However Wilkins' unconfined B_4C is not as strong as

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tested here. This suggests that surface defects distinguish the “old” and new B_4C [1].

- The agreement in failed strength using different test techniques and procedures, e.g. present study, Meyer and Faber, and Wilkins', suggest that the response of the damaged B_4C is providing the fundamental behavior of the damaged material as a function of confinement.
- Confinement pressures are not sufficiently high to achieve a definitive cap on the damaged B_4C . However, work by Walker [37] suggests a cap of 4.0 GPa and the experimental data here are consistent with Walkers' finding.
- The overlap of Paris results with the other data suggests little or no strain rate effect for the compressive strength of damaged B_4C . The one data point using the SHPB is consistent with this interpretation.
- Intact data from unconfined, quasi-static confined (Wilkins) and divergent flyer-plate technique provides an upper envelope of the strength of intact B_4C .

4.0 Results on Silicon Carbide

4.1 Introduction

Silicon carbide (SiC) specimens were tested using the same experimental technique as for B_4C , but the response is very different. Intact unconfined SiC specimens were tested by Dannemann et al. [25] in 2004 with strengths up to 6 GPa, close to our MTS machine limit. Hence compression of intact specimens under confinement was not considered, as specimen strength increases significantly under pressure and, thus, the strength of confined SiC would be above our machine limits.

Compression of predamaged specimens was accomplished at confinement pressures up to 350 MPa. One of the specimens was tested under triaxial tension with a confinement pressure of 500 MPa, but the specimen did not fail. Three specimens were tested in compression inside the steel sleeve although these tests provided only two failure points. Table 4 provides a summary of all the SiC tests performed in this program. All the tests were conducted at quasi-static strain rates.

Table 4. Silicon Carbide – Test Summary.

Specimen	Test type	Confinement Pressure (MPa)	Specimen initial condition	Specimen	Test type	Confinement Pressure (MPa)	Specimen initial condition
SC-03	Triaxial	50	Predamaged	SC-09	Triaxial	350	Predamaged
SC-04	Triaxial	50	Predamaged	SC-10	Triax.-tension	500	Predamaged
SC-05	Triaxial	150	Predamaged	SC-11	Sleeve	n/a	Predamaged
SC-06	Triaxial	150	Predamaged	SC-12	Sleeve	n/a	Predamaged
SC-07	Triaxial	350	Predamaged	SC-13	Sleeve	n/a	Predamaged
SC-08	Triaxial	350	Predamaged				

Dannemann et al. [25] reported initial sleeve test results on predamaged SiC in 2004. For consistency, the data from the 2004 tests were reanalyzed, and are combined with the new data; results are presented below.

4.1.1 Triaxial Compression Tests of Predamaged Specimens

Triaxial compression testing of the predamaged SiC specimens was conducted similarly to the B_4C specimens. The first striking difference between the experimental results can be observed in Figure 13(a) for SiC. In Figure 7, B_4C showed load carrying capability even after failure, while SiC fails and shatters. Upon SiC failure, the brass foil and Teflon sleeve that surrounds the specimen are punctured so the specimen loses integrity and its load carrying capability goes immediately to zero. This is presumably due to the higher elastic energy stored in the specimen at failure. At failure, release of the elastic energy drives the fragments through the surrounding sleeve.

Figure 13(a) shows that the loading process is linear up to failure except for an initial non-linearity, probably due to a small non-linearity in the load cell at very low axial loads. Failure loads are plotted in the equivalent stress vs. pressure graph in Figure 13(b) as solid blue circles. Test SC-03, performed under a confinement pressure of 50 MPa, is shown as an open blue circle. This test was unexpectedly strong for a low confinement pressure and, as shown in the figure, lies almost on the intact line (line of slope 3). It was not included in the linear regression

analysis. Figure 13(b) also displays data from Ref. [25] for intact, unconfined SiC specimens (open red diamonds) and predamaged unconfined specimens (solid blue triangles). The scatter on the unconfined data is large: from 4.3 to 6 GPa for the compression strength of intact specimens and from 2 to 3.9 GPa for predamaged specimens.

The comparison between unconfined predamaged and confined predamaged data provides a consistency check. The linear regression performed on confined predamaged tests gives the strength of the material as a function of confinement pressure, and should intersect the slope 3 line at zero confinement pressure. Therefore, if the triaxial results are consistent with the unconfined results, the intersection should be at an “average” value of the unconfined strength. Extrapolation of the linear regression to the slope 3 line gives $\sigma_{eq} = 3.2$ GPa, while the average value found for the strength of unconfined predamaged specimens is 3 GPa, in good agreement.

Only one test (SC-10) was performed under triaxial tension. The maximum confinement attainable in our pressure vessel (500 MPa) was applied to increase the likelihood of failure. It was not possible to fail the specimen, implying that predamaged SiC can take at least 500 MPa in tension. Nevertheless a non-linearity in the axial-stress vs. axial-strain curve was observed around 200 MPa (0.09% axial-strain). The origin of the non-linearity is unknown, but the specimen recovered after the test had structural integrity. No pre- or post-test imaging of the specimen was performed to see if the amount of damage had increased.

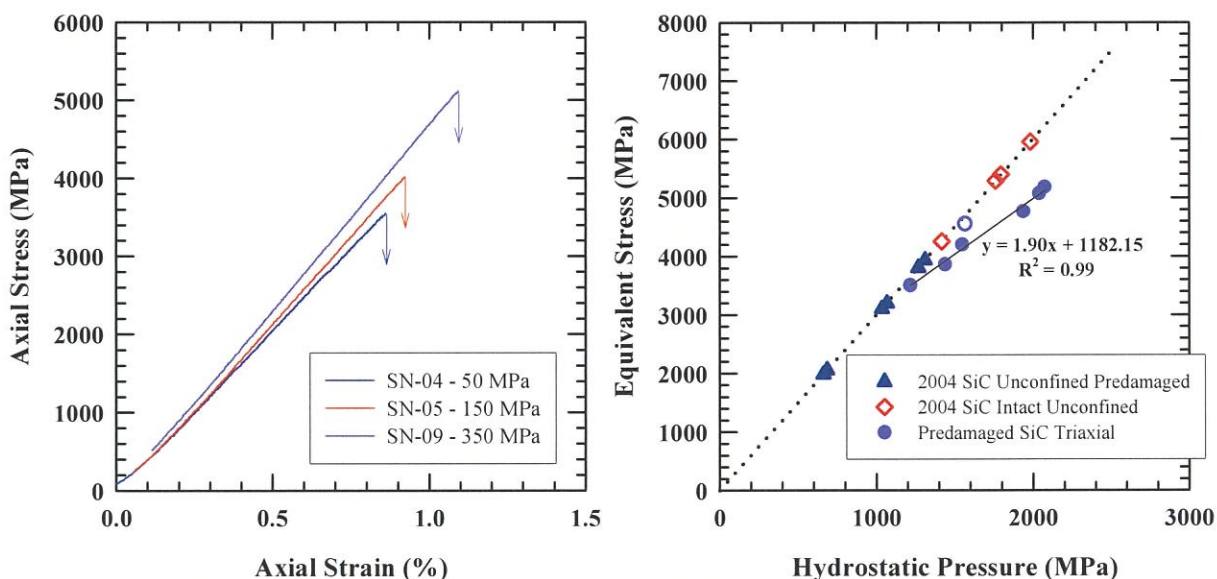


Figure 13. a) Triaxial compression of predamaged SiC specimens at different confinement pressures. b) Failure stress for intact and predamaged SiC

4.1.2 Confined Sleeve Tests of Predamaged Specimens

Very limited data were obtained when the predamaged specimen was confined in the sleeve due to the high strength of SiC. The sleeve, when appropriately honed to fit the specimen, provides enough confinement to the predamaged specimen that it is not possible to fail it, even when applying multiple loading cycles at progressively higher loads. The number of load cycles for tests SC-11, 12 and 13 were 9, 8, and 9, respectively. Sudden jumps in hoop strain, indicating failure, were only observed once in test SC-11 and once in test SC-12. Figure 14(a) shows the load curves obtained for specimen SC-12; and the failure point or sudden jump is

highlighted with an arrow (at 0.0005 strain). The only jumps that are considered failures are the ones that either maintain or decrease the load carrying capability. A small jump like the one that happens at a hoop strain of 0.00042 where the load increases, is not considered a failure point and is not plotted in Figure 14(b).

Figure 14(b) shows that only two failure points (solid red squares) were obtained from the three sleeve tests performed. The two red square data points obtained are at low confinement pressures (approximately 150 MPa). This is due to the combination of high elastic modulus and high strength of SiC. The axial load needs to be very large to create a small radial displacement. The confinement pressure produced by the sleeve is proportional to the radial displacement, and, consequently, the confinement pressure stays small. The sleeve technique is most appropriate for materials with lower elastic modulus and/or strength. Although B₄C is also a high modulus material, its strength is considerably less than that of the SiC.

Figure 14(b) also includes “old” data (triangles) from 2004 investigations by Dannemann et al. [25]. These are weaker than the specimens tested for the present work. The reason is not well understood but it is probably due to specimen failure before full confinement is provided by the sleeve. As was learned with testing of glass [26], the sleeve needs to be honed precisely for each individual specimen to provide appropriate confinement.

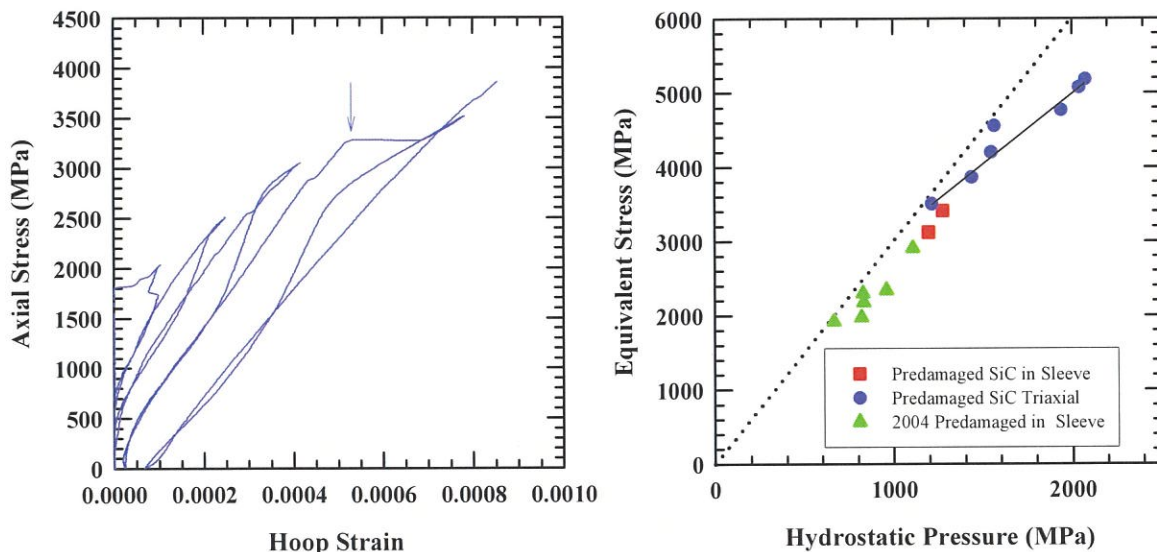


Figure 14. a) Example of the axial-stress vs. hoop strain load curves for specimen SC-12, b) Sleeve and triaxial data for predamaged SiC specimens are compared.

4.2 Discussion of Silicon Carbide Results

Since silicon carbide has important applications it has been tested both with and without confinement by many researchers. The literature data presented in Figure 15 are from Johnson et al. [4], Pickup and Barker [38], Lee et al. [39], and Paris et al. [24]. All the unconfined data lie on the slope 3 line. The data that are to the right of the slope 3 line are from confined tests.

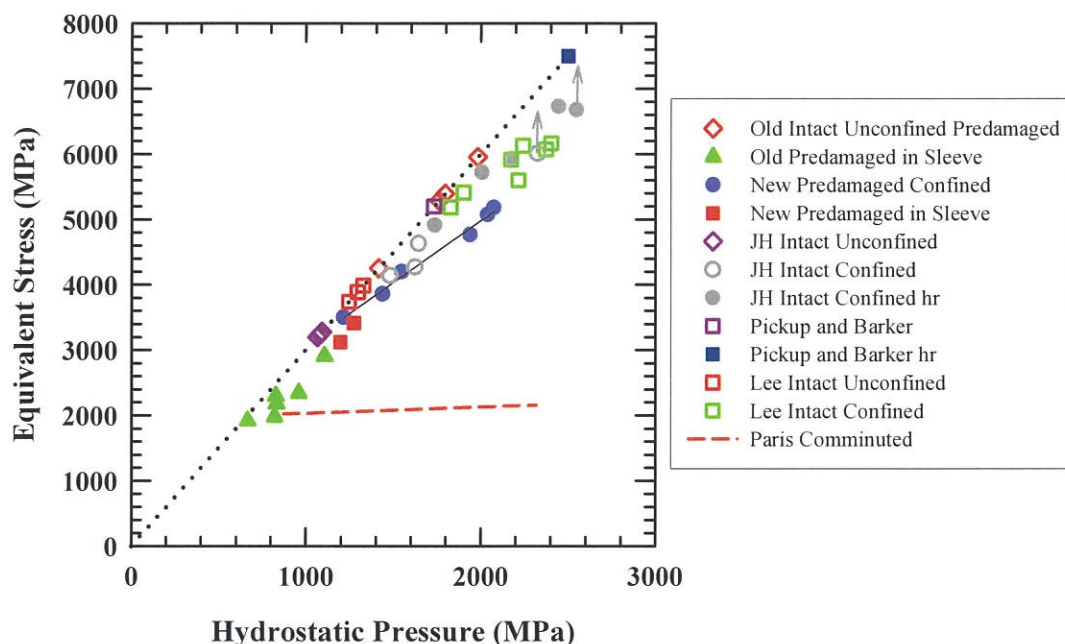


Figure 15. Comparison of the data obtained during this project with the SiC data found in the literature. The arrows indicate that the specimen did not fail. (hr=high rate).

The first remark is that the intact unconfined strength spans from 3.2 to 6 GPa. For a high rate test (denoted “hr” in the legend) the strength was up to approximately 7.5 GPa. Johnson et al. [4], used α -sintered silicon carbide, which has a lower strength than the SiC-N that was used by Dannemann et al, or Lee et al. Pickup and Barker tested three different types of SiC but the two points presented in the plots are for the pressureless sintered variety, one at low and one at high strain rate. Their low strain rate data matches Dannemann’s data although the latter data set has large scatter.

Johnson et al.’s confined intact data, shown in Figure 15, consists of low rate and high rate data. On average, high rate data (solid gray circles) are stronger than low rate data (open gray circles) although one of the low rate data did not fail (open gray circle with arrow indicating it is a minimum value). Johnson’s high rate data overlaps Lee’s data but it should be noted that Lee’s data are quasistatic. This might be another indication that Lankford’s [7] hypothesis is true, i.e. the ultimate strength for strong ceramics is controlled by the yield point, if it can be reached. High confinement and high strain rate (“crack confinement”, as he states) help to reach the yield point.

Figure 15 also shows SiC data for comminuted specimens (dashed line) tested under divergent plate impact by Paris et al. [24], who used α -SiC. The data are presented as a dashed line because the response is calculated by matching waves recorded in the plate impact test with a failure model assumed for the specimens. For low pressures, their data overlap the test results for predamaged SiC specimens in the sleeve. For higher pressures, the Paris’ data are much lower than the predamaged data obtained in this project. There could be multiple reasons, which will be discussed at the end of the next subsection.

For completeness, a figure with only the intact data is presented; see Figure 16. This figure presents higher pressure flyer-plate impact data have been added from Bless, Grady, and Klopp as cited by Johnson et al. [4]. Divergent plate impact data for intact SiC has also been added

from Paris [24]. The short dashed-blue curve is an envelope of the data. The dash-dot blue line is from a curve fit that Lee et al. [39], provides that encompasses his and Vogler's, both for SiC-N.

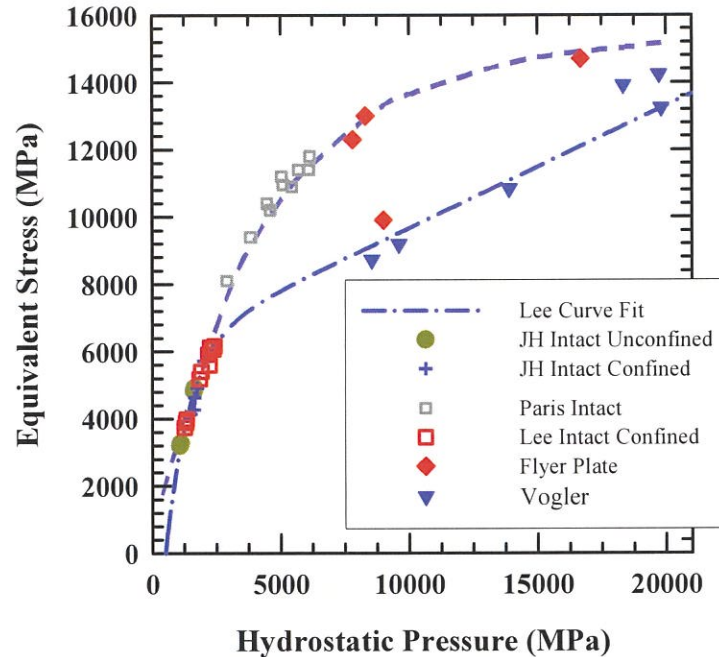


Figure 16. Quasistatic and flyer-plate impact data for intact SiC.

4.3 Comparison of B₄C and SiC

Figure 17 compares intact unconfined and predamaged confined tests performed on SiC and B₄C. The average strength measured in the tests for intact B₄C and SiC is 3.5 GPa and 5.2 GPa, respectively. SiC is approximately 50% stronger than B₄C as an intact specimen.

The predamaged numbers are very different. If the linear interpolations shown in Figure 17 are extrapolated to the left until intersecting the slope 3 lines, in theory they should intersect at a point that should be the average strength of a predamaged unconfined ceramic. For B₄C the intersection point is ~1 GPa while for SiC ~3.3 GPa. This means that, in the damaged unconfined state, SiC is more than three times stronger than B₄C, i.e. B₄C has more damage than SiC. Since the slopes are not very different (~1.8 for B₄C and ~1.9 for SiC) the difference will be maintained even at high pressures. Measuring the amount of damage or cracks introduced in the specimens through the thermal shock procedure is difficult, but the ratio of damaged to intact strength in compression could be a quantitative measure of damage. So, for example, damage on SiC could be quantified as:

$$D_{\text{SiC}} \approx (1 - 3.3/5.2) = 36.5\% \text{ and for boron carbide } D_{\text{B}_4\text{C}} \approx (1 - 1/3.5) = 71\%.$$

It is interesting to note that Figure 2(b) visually shows the damage on the B₄C specimen after the thermal shock procedure. The amount of damage is clearly larger than for SiC, as seen in Figure 1. This preliminary analysis is suggestive that a quantitative measure of the amount of damage can be obtained.

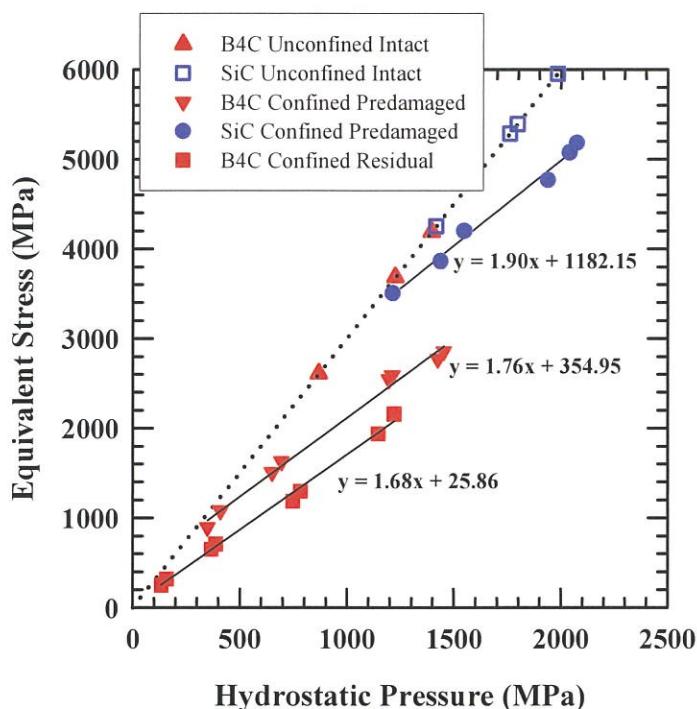


Figure 17. Comparison of B₄C and SiC results.

Paris et al.'s data for comminuted SiC falls considerably below the confined predamaged SiC data, Figure 15; yet, Paris' B₄C data were in reasonable agreement with the predamaged B₄C data plotted in Figure 11. There are several possibilities for this discrepancy, and one of these is suggested by the large difference in D_{SiC} and D_{B4C} . For B₄C, it was possible to load/reload the confined specimens so that the strength of highly comminuted B₄C was interrogated by the test. The confined predamaged SiC still had sufficient strength that stored elastic energy tore the Teflon sleeve in the triaxial compression tests. For the confined sleeve tests, even though the SiC was predamaged, it was still extremely difficult to produce further damage, i.e., the maximum force that could be exerted by the MTS machine was not adequate to induce further damage easily to the SiC specimens. Thus, the confined SiC test results do not represent the response of comminuted SiC.

The above explanation is speculative. Walker's analysis [37] suggests that the cap for comminuted SiC is 3.7 GPa, and Paris' results are considerably below this value. Thus, the discrepancy could possibly be the result of Paris' modeling assumptions. Clearly, further work is required to understand more fully the response of comminuted SiC.

5.0 Post-Test Evaluation

Post-test evaluations were conducted on select B₄C and SiC-N specimens. The extent of damage and possible damage modes were compared for the two materials. Specimens were chosen to allow comparison of the two materials at similar test conditions, and for a range of confining pressures. Optical and stereomicroscopy were used to evaluate and document the damage. Specimens were carefully handled and prepared to limit further damage following testing. The steel sleeve, or Teflon sleeve, was removed to view the damage *in-situ*. Removal of a “pie section” along the entire length of the steel confining sleeve allowed viewing of the damage along the entire specimen length with minimal disturbance to the specimen. The location of the opening was chosen based on viewing the damage at the ends of the specimen. For the triaxial tests, slitting and opening of the Teflon sleeve allowed improved views of the damaged regions. Details on the preparation techniques are presented in Ref. [33].

5.1 B₄C Specimens

5.1.1 Intact

A qualitative difference between the failure of intact and predamaged specimens was discussed in the B₄C section. This is evident in the plot in Figure 7, upon comparison of the triaxial compression test results for intact vs. predamaged B₄C. Post-test evaluations of the specimens also highlighted differences in damage features for the two material conditions. The photos in Figure 18 for specimen BC-02 are representative of the behavior of the *intact* B₄C specimens following triaxial compression.

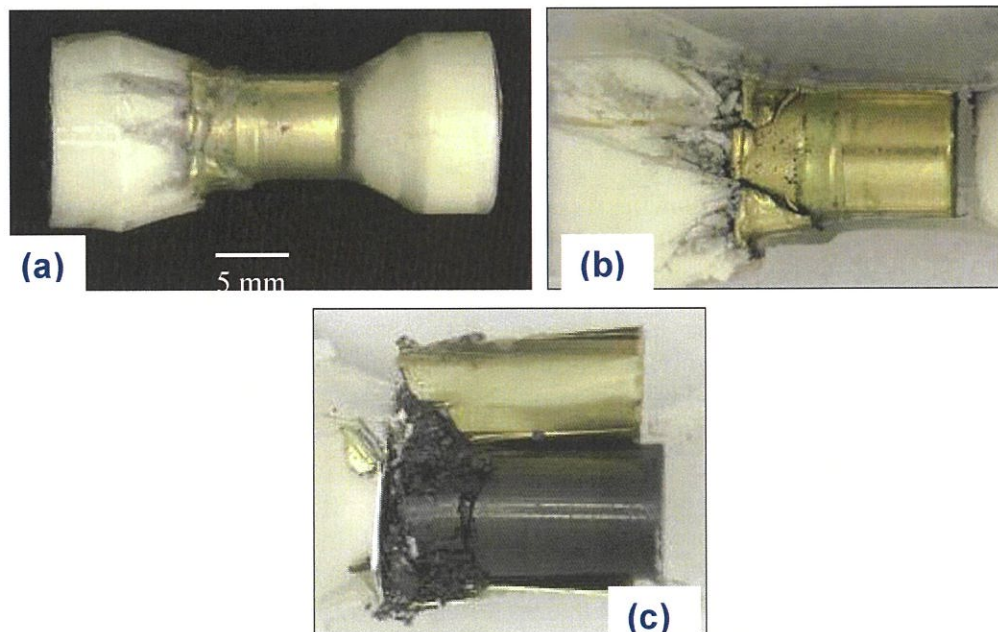


Figure 18. Specimen BC-02 (intact) following triaxial compression testing with 50 MPa confinement pressure. Specimen failure also resulted in failure of the anvils.

Failure of the intact specimen occurs due to loading and is accompanied by failure of the alumina anvils. Anvil failure is apparent in Figure 18(a). Much of the specimen remains intact (Figure 18c) following testing at a confinement pressure of 50 MPa.

5.1.2 Predamaged

Predamaged B₄C specimens were investigated following triaxial compression and tension tests, and following compression tests with a steel confining sleeve. Post-test evaluations of B₄C compression test specimens revealed the presence of a dominant slip plane in all specimens. The orientation of the slip plane was quite consistent. The angle between the slip plane and the compression loading axis ranged from approximately 23° to 37°, regardless of the confining pressure. The slip plane is readily apparent at low and high confining pressures. Representative photos are shown in Figure 19 for the range of confining pressures obtained. Damage likely initiates on pre-existing cracks formed during the thermal shock procedure.

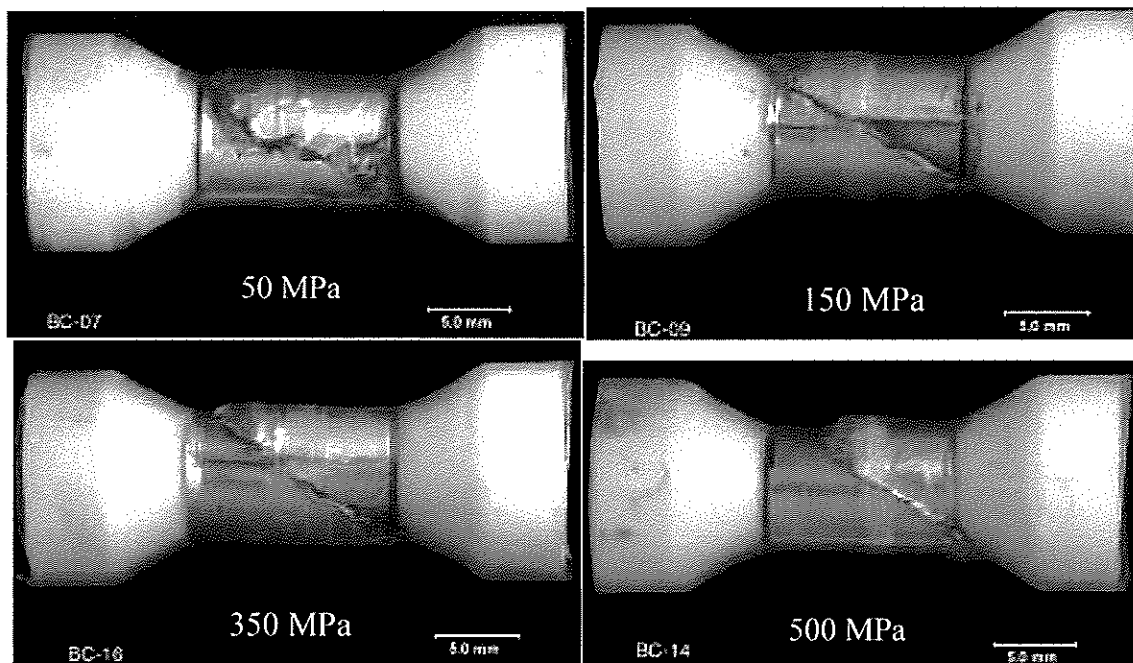


Figure 19. B₄C specimens following triaxial compression tests with confining pressures of (a) 50 MPa, (b) 150 MPa, (c) 350 MPa, (d) 500 MPa. The angle of the slip plane is similar for all pressures evaluated.

Slitting of the Teflon sleeve, and opening of the brass foil, revealed additional damage features of the tested specimens shown in Figure 19. These can be viewed in Figure 20. The slip plane is not as apparent for the low confining pressure tests (e.g. Specimen BC-07, 50 MPa). However, the tape that holds the brass foil onto this specimen remained in place, and is visible in the center of the specimen, shown in Figure 20a; this masks part of the slip plane. The extent of damage in the vicinity of the slip plane appears to diminish with confining pressure, as illustrated by the representative specimens shown in Figure 20. Specimen BC-07 has more loose particulates than Specimen BC-14 (confining pressure = 500 MPa). Specimen BC-14 remained more “intact” than the other B₄C specimens tested at lower confining pressures. This is consistent with the test results plotted in Figure 7, where an increased confining pressure results in increased residual strength.

As discussed in the B₄C section, triaxial tests conducted in tension resulted in a very different failure mode vs. the triaxial compression tests. The failure stress does not seem to depend on the confinement pressure for the triaxial tension tests. Examination of the two specimens tested in

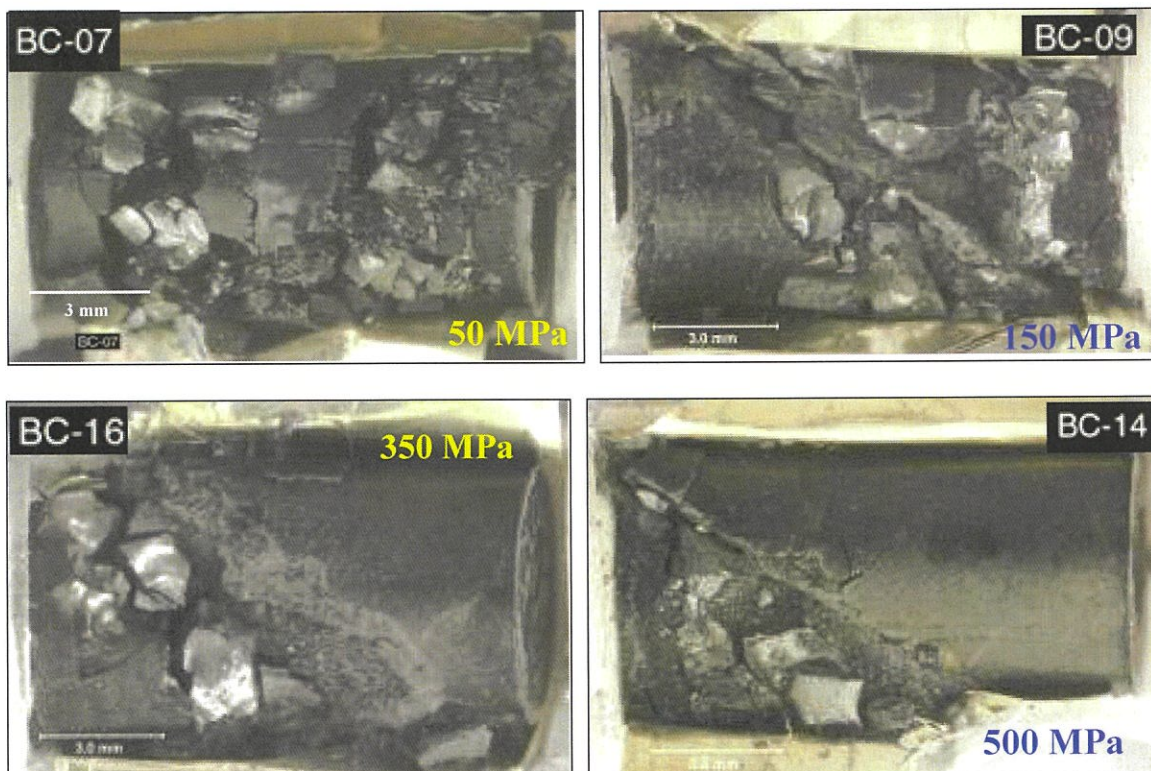


Figure 20. B₄C specimens in Figure 19 after removal of Teflon sleeve, and tested at confining pressures of (a) 50 MPa, (b) 150 MPa, (c) 350 MPa, (d) 500 MPa.

tension support the explanation provided in the B₄C section. When the specimen fails, cracks form perpendicular to the long axis of the specimen. Note the jagged crack located near the center of the specimen (BC-18) shown in Figure 21. This was also observed for specimen BC-17, tested in triaxial tension. Upon relief of the axial stress, further separation of the ceramic fragments occurred as shown on the right side of the specimen.

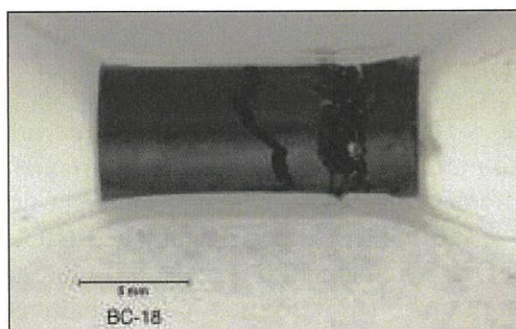


Figure 21. B₄C specimen (BC-18) following triaxial tension testing. The specimen fractured at two different locations. The fracture planes are oriented perpendicular to the loading direction.

The data presented in Section 3.3 for the confined sleeve experiments on predamaged B₄C specimens indicate a similar or greater strength for the confined sleeve tests in compression vs. the triaxial compression tests. The failure mechanisms are assumed to be similar (i.e., formation of a dominant slip plane with movement of the fracture surfaces initially controlled by frictional forces due to a rough surface condition). The post-test condition for two of the sleeved specimens (BC-19 and BC-25) is illustrated in the photos in Figure 22. The extent of damage was less than that observed for the specimens tested in triaxial compression (compare Figure 22 and Figure 20), although BC-19 and BC-25 were tested at high confinement pressures (~1 GPa). Some fragmentation was observed near the ends of the confined sleeve specimens. Closer examination of the specimen surfaces revealed cracking (not readily visible in the photographs), with more cracking for the specimen with 7 load/reload cycles. Shear planes are more readily visible in Figure 22(b). The higher confining pressure limits the amount of shear that can occur in the confined sleeve specimens, and contributes to the strength enhancement. It is likely that damage to the confined sleeved specimens accumulates internally until a critical level is reached; specimen fragmentation and failure ensues. Sectioning of the specimen is required to confirm this hypothesis.

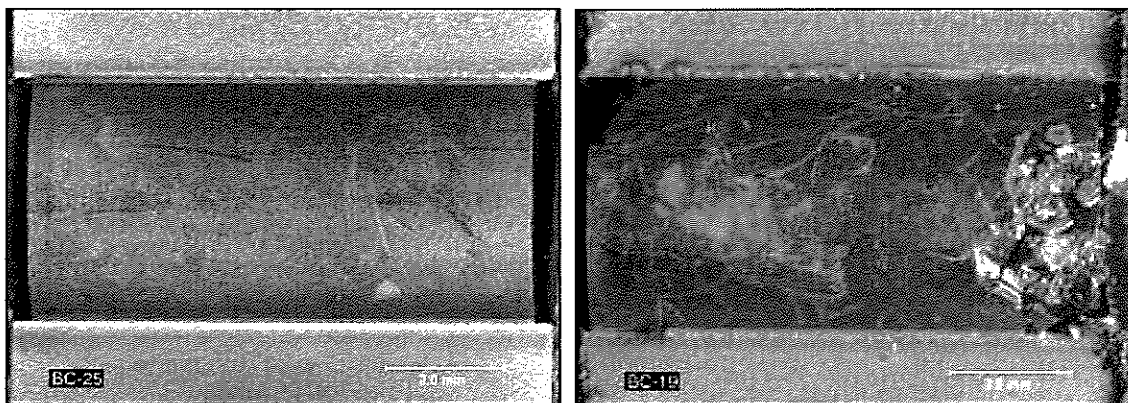


Figure 22. B₄C specimens tested with mechanical confinement following removal of a section of the steel sleeve to view specimen damage. Test parameters were: (a) BC-25: two load/reload cycles loaded to a maximum axial stress of 1.0 GPa, (b) BC-19: seven load/reload cycles loaded to a maximum axial stress of 4 GPa.

5.2 SiC Specimens

Post-test evaluations were also performed on predamaged SiC-N specimens following confined compression testing. This includes specimens tested with hydraulic confinement, as well as specimens tested with mechanical confinement. The triaxial compression test results for the SiC material showed differences vs. B₄C, which is apparent upon comparison of the axial stress-strain plots in Figure 7 and Figure 13 for predamaged B₄C and SiC, respectively. The axial stress-strain curves for SiC remained linear until failure, whereas the B₄C material maintained some load carrying capability after initial failure. Failure of the SiC specimens is due to the stored elastic energy tearing the sleeve upon failure, so the specimen could not carry a residual load.

Visual evaluation of the SiC triaxial compression specimens following testing did not reveal any obvious differences between the two materials. The SiC specimens also exhibited a dominant shear plane, similar to that observed for the B₄C specimens. The shear angles measured for the two materials were similar (i.e., approximately 25-40°). Photos of

representative SiC specimens following triaxial compression testing are shown in Figure 23. Note the similarities for the SiC specimens vs. the B₄C specimens shown in Figure 19. Failure of the plastic holder occurred for the SiC test specimens, but not the B₄C specimens. There is not a comparison photo for SiC at 500 MPa as triaxial tests were not performed on the SiC material at this pressure.

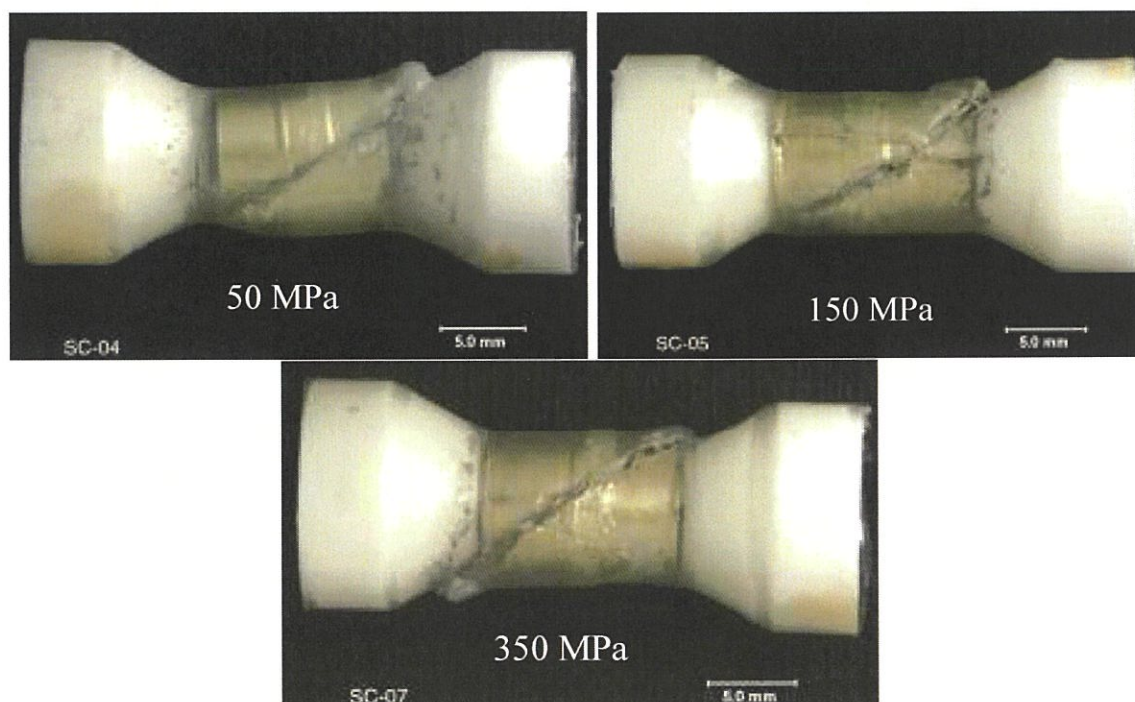


Figure 23. SiC specimens following compression tests with hydraulic confinement at pressures of (a) 50 MPa, (b) 150 MPa, (c) 350 MPa. The shear angle is similar to the B₄C samples.

However, differences between the SiC and B₄C triaxial compression specimens were apparent upon viewing the specimens with a stereomicroscope following removal of a section of the Teflon sleeve and brass foil. The SiC specimens exhibited clean fractures along the dominant shear plane with large fragmented regions adjacent to this plane. This is illustrated by the photos in Figure 24 which correspond to the specimens shown in Figure 23. Some particulates were also observed in the vicinity of the shear plane; these are likely residue from the cracks. The smoothness of the observed cracks indicates that the fracture process occurred rapidly. This is consistent with the linear stress-strain curves exhibited by these specimens (Figure 13), which indicates that failure occurs instantaneously. The large fragments adjacent to the slip plane in the SiC specimens result from the growth of a limited number of pre-existing cracks due to the thermal shock procedure (e.g. Figure 1). The fracture appears more violent at the highest (350 MPa) confinement pressure evaluated, as evidenced by the presence of more fragments and out-of-plane shifting of the larger fragments (see specimen SC-07, Figure 24(c)). Damage was observed throughout the SiC triaxial compression specimens shown in Figure 24. In contrast, damage to the B₄C specimens was concentrated in the vicinity of the dominant shear plane.

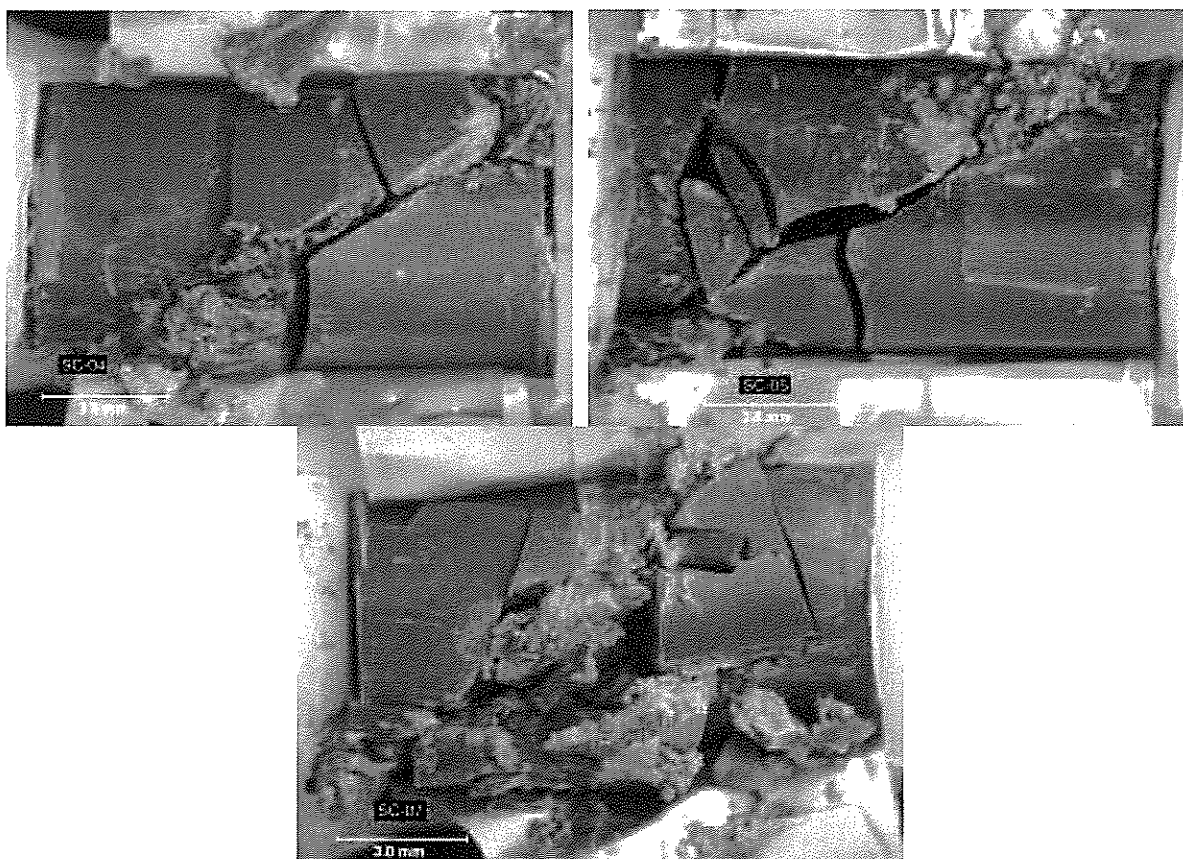


Figure 24. SiC specimens in Figure 23 after removal of Teflon sleeve, and tested at confining pressures of (a) 50 MPa, (b) 150 MPa, (c) 350 MPa.

Examination of the SiC confined sleeve specimens following testing revealed similar damage patterns to the triaxial compression specimens. Large cracks were detected in the two SiC specimens evaluated following removal of a lengthwise section of the steel confining sleeve. Illustrative photos of these specimens are shown in Figure 25. There is evidence of crack initiation along a shear plane, though the shear plane is not as well defined or with as steep an angle as for the triaxial compression specimens. For specimen SC-12 shown in Figure 25, the transverse cracks cross the shear crack with minimal displacement of the transverse crack faces. This implies the transverse cracks progressed before much shearing could occur. In contrast, Specimen SC-11 shows a displacement of a single transverse crack across the shear crack. The extent of transverse cracking is less for Specimen SC-11 vs. SC-12 although it experienced an extra loading cycle. Again, the transverse cracks likely initiated from pre-existing cracks in these specimens due to the thermal shock procedure. The cracks observed in the sleeved specimens had wide crack opening displacements with few, if any, particulates between the crack faces. This is indicative of brittle fracture. The sleeved SiC specimens fractured quickly as the specimens were loaded, with a corresponding increase in pressure. The crack patterns also differed for the sleeved B_4C and SiC specimens. Compare Figure 22 and Figure 25. Cracking was more extensive for the sleeved SiC specimens probably because of low confinement pressure.

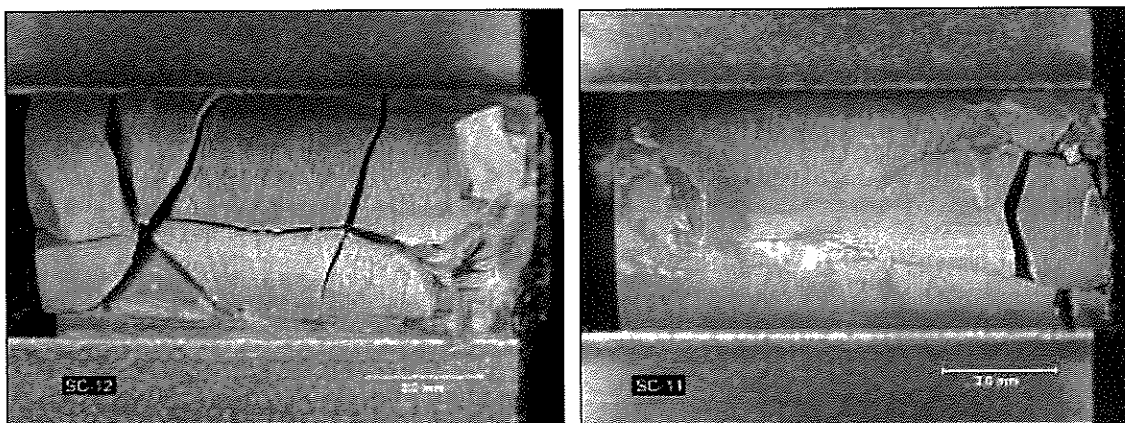


Figure 25. SiC specimens tested with mechanical confinement following removal of steel section to view specimen damage. Test parameters were: (a) SC-12: eight load/reload cycles loaded to a maximum pressure of 3.9 GPa, (b) SC-11: nine load/reload cycles loaded to a maximum pressure of 4.3 GPa.

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6.0 Summary Tables with Properties for Boron Carbide and Silicon Carbide

In this section a summary of the constitutive laws, Drucker-Prager and Mohr Coulomb, derived for boron carbide and silicon carbide are provided. The Drucker-Prager model is used extensively in hydrocodes (e.g., CTH [40], LS-DYNA [41]) when there is need to simulate materials where the strength increases with the pressure. The flow surface is a cone in the principal stress space and the projection on the π -plane (a plane with normal (1,1,1)) is a circle. According to Drucker-Prager the strength varies linearly with pressure:

$$Y = Y_0 + \beta P$$

where Y_0 is the strength at zero pressure and β the slope. Some materials have a cap, i.e. the strength cannot increase monotonically and, at some pressure, the strength reaches a plateau $\bar{Y}$. The reason for Drucker-Prager wide use is because it is the simplest way (linear) to introduce pressure dependence in a constitutive model. Additionally it has a smooth flow surface without cusps, making it suitable for relatively easy implementation and applicability for numerical simulations.

Geological materials, ceramics, concrete, etc., become stronger at higher pressures. The variation of the strength as a function of pressure for boron carbide and silicon carbide was explored using SwRI's triaxial compression apparatus. Drucker-Prager constants are readily determined once the equivalent stress vs. pressure plot are created as in Figure 8(a), for example. The linear regression gives the values presented in Table 5 and Table 6.

Table 5. DP Parameters for Intact and Predamaged B₄C ($Y = Y_0 + \beta P$)

Specimen	Bomb Tests		Sleeve Tests	
	Y_0 (GPa)	β	Y_0 (GPa)	β
Intact	1.5	1.9	—	—
Predamaged	0.35	1.8	0.60	1.4
Residual	0.026	1.7	—	—

Table 6. DP Parameters for Predamaged SiC ($Y = Y_0 + \beta P$)

Specimen	Bomb Tests	
	Y_0 (GPa)	β
Predamaged	1.2	1.9

The Mohr-Coulomb constitutive model is also provided because, on theoretical grounds, ceramics are expected to follow this model when a simplified sliding crack model for brittle failure is assumed, see Ashby and Sammis [42] as cited by Chen and Ravichandran [11]. Additionally the Mohr-Coulomb criterion provides, at least qualitatively, the correct failure pattern for the specimens tested in the pressure vessel under confinement. In the principal stress space, the failure surface constitutes a hexagonal cone, and in the π -plane it is an irregular hexagon.

Table 7 and Table 8 summarize the Mohr-Coulomb constants obtained for the tests on B₄C SiC. The reader is referred to [25] for a detailed explanation on how to obtain these constants.

Succintly explained, plots of the radius ($R = (\tilde{\sigma}_1 - \tilde{\sigma}_3)/2$) vs. center ($C = (\tilde{\sigma}_1 + \tilde{\sigma}_3)/2$) of the Mohr circle at failure are graphed and a linear regression is performed through all the points in the plot. The slope of the regression line is equal to $\sin(\phi)$ where ϕ is the angle between the yield locus (in the τ vs. $\tilde{\sigma}_n$ plane), i.e. $\mu = \tan(\phi)$ is the slope of the Mohr-Coulomb line as shown in Figure 26(a). The linear regression of R vs. C also provides the cohesion coefficient, c , since it intersects the y -axis at $c \cos(\phi)$, see Desai [30].

Table 7. MC Parameters for Intact and Predamaged B₄C ($\tau = c + \mu \tilde{\sigma}_n$).

Specimen	Bomb Tests			Sleeve Tests		
	c (GPa)	μ	α	c (GPa)	μ	α
Intact	0.84	1.1	22	—	—	
Predamaged	0.19	0.93	24	0.28	0.72	27
Residual	0.013	0.87	25	—	—	

Table 8. MC Parameters for Predamaged SiC ($\tau = c + \mu \tilde{\sigma}_n$)

Specimen	Bomb Tests		
	c (GPa)	μ	α
Predamaged	0.71	1.0	22

The expected failure angle (Nedderman [32], Wilkins [2]) is $\alpha = 45 + \phi/2$ when measured from the vertical axis. Figure 26(b) shows the principal stresses ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) on the specimen. In this figure the stresses are positive in tension, hence the axial load is the least principal stress because it is the largest negative value. Table 7 reports the angles expected for the different specimens. As mentioned previously (e.g., see Fig. 19) the angle measured experimentally was between 23 and 37 degrees, so the angle provided by the Mohr-Coulomb model is within the range of expected angles.

For SiC the angle derived from the Mohr-Coulomb model is 22 degrees while experimentally the angles measured are between 25 and 40 degrees. The model provides an angle slightly lower than the experiments but the small difference is probably due to experimental scatter.

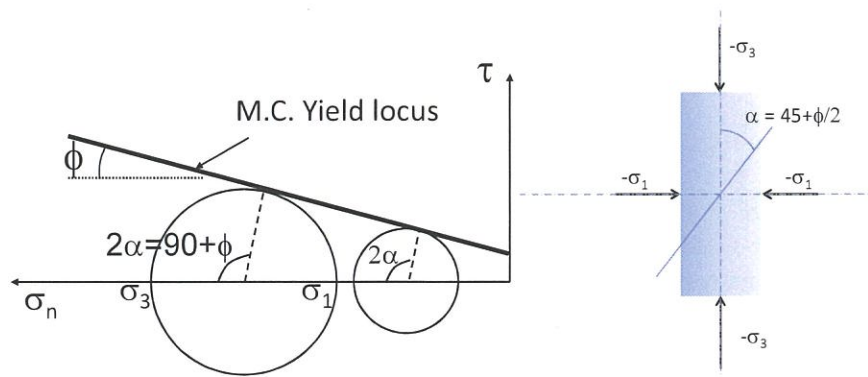


Figure 26. a) Mohr-Coulomb yield locus, b) Schematic of the stresses applied on the specimen in the triaxial test.

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