OPTIMIZING THE FIBER PUSH-OUT METHOD TO EVALUATE INTERFACIAL FAILURE IN SiC/BN/SiC CERAMIC MATRIX COMPOSITES

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Funding information
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Abstract
The investigation of several parameters during fiber push-out micromechanical tests on the interfacial shear strength (ISS) of the BN interphase in SiCf/SiC ceramic matrix composites (CMC) was undertaken to optimize experimental work. The SiCf/SiC composites—candidate materials for jet engine components—were manufactured with varying fiber types and interlayer thicknesses. Experimental parameters explored included analyzing the effect of sample thickness on the success rate of micromechanical tests, the effect of fiber local environment whether at tow-level (intra-tow variability in ISS) or CMC architecture-level (inter-tow variability), the effect of nanoindenter flat-punch tip size, and the effect of the interphase thickness itself. Over 1000 fiber push-outs were performed and analyzed in this work—with data presented as cumulative distribution functions to compare and contrast samples. It was found that the ISS measured was strongly and statistically influenced by the underlying fiber roughness (interphase adherence), as well as its local fiber environment (e.g., number of nearest neighbors) only if the thickness of the interphase itself surpassed a threshold of 200 nm. Finally for thinner interphases, limited value was added to the CMC as the ISS measured was high and there was no effect from any local environment.

KEYWORDS
boron nitride, ceramic matrix composites, fibre push-out, interfacial, micromechanics, silicon carbide

1 | INTRODUCTION

Typical ceramic matrix composites (CMCs) consist of long fibers imbedded in a matrix, bonded by an interphase.1–3 The most common CMCs make use of carbon, alumina, or silicon carbide (SiC) fibers incorporated in an alumina, Carbon, SiC, or mullite matrix.4 These CMCs have found use in multiple markets (automotive, nuclear, and friction systems)1 over the years for their high-performance mechanical and thermal properties such as low coefficient of thermal expansion, high specific stiffness, and increased damage tolerance (notch insensitivity).5 Ceramic matrix composites have distinct toughening mechanisms (including fiber pull-out) giving their fracture behaviour a quasi-brittle/pseudo-ductile response.6 Fiber pull-out makes use of an interlayer between the fiber and matrix with distinct tribological properties, which enable transfer of load from one to the other.7 The interphase material needs to be thin enough (less than a micron thick—usually...
a few hundreds of nm), have low fracture toughness or low shear strength for fiber pull-out to take effect. The 2D planar interface between the interphase (usually pyC or BN) and the fiber directly correlates to specific composite characteristics such as the residual clamping stress and the fiber roughness—both of which increase the frictional resistance.8

Ceramic matrix composites fail by cohesive (strong interfaces, short cracks within the interphase, matrix load sharing, matrix cracking with significant energy hysteresis during macro-failure,9 failure is initiation controlled) or adhesive (weak interfaces, fiber de-bonding, crack bridging, fiber pull-out, slip with no to little friction and little hysteresis in macro-failure,10 failure is propagation controlled) modes as highlighted in Figure 1.

The composites in this work focus on use SiC-based fibers imbedded in a SiC matrix with a BN interphase to link the two. BN is the preferred coating for applications where oxidation can occur in high-temperature environments, including aero-engines. NASA revealed that pyC-based interlayers degrade and oxidize very quickly from interactions with the combustion gases11—with losses characterized as catastrophic12 at temperatures ranging from 500°C to 1000°C. In BN interphases, the more stable Boria is formed over a wide range of temperatures (600-1200°),13 but is nevertheless subject to “pest” oxidation whereby oxidation nurtures environmentally assisted cracking at intermediate temperatures (500°C–1000°C) and high stresses (Over 100 MPa).14,15

In SiC/BN/SiC composites, three major companies (Nippon Carbon, ATK-COI Ceramics, and Ube Industries) have been producing three standout types of fibers (Hi-Nicalon type S, Sylramic-iBN, and Tyranno SA3, respectively) usually made with different sintering aids, and therefore exhibiting slightly different properties. Both second- and third-generation Tyranno type SA fibers were found to be significantly rougher than second-generation Hi-Nicalon fibers16 but in general are half the diameter, have more residual carbon and larger β-SiC crystals than Hi-Nicalon type S fibers.17,18

Current ongoing research in engineering techniques to tailor the interphase for a better control of its micromechanics include tempering the interface by doping,19,20 multi-layering13,21,22 or fugitive interfaces,23,24 or modifying the processing conditions,25–27 However, this requires a reliable and quantifiable method of measuring interfacial properties, especially if microstructurally informed rather than empirical methods are to be developed.

Extracting interfacial properties of composites has proven to be a major engineering challenge in materials science. A few meso-scale and macro-scale techniques highlighted by Bansal and Lamon28 such as the transverse bend test or the Brazilian disc compression test extract interfacial properties from data fitting; these techniques have shown experimental reproducibility but are unsupported by sufficient modeling. Micro-mechanical tests help reveal intrinsic properties (and in the case of composites, the properties of each constituent rather than the property of the composites as a whole) and are usually conducted on coupons which are easier to test for fundamental understanding of the CMC mechanisms—while also reducing costs of testing as sample sizes for destructive evaluation are smaller than macro-scale experiments. Micro-mechanical techniques yield useful metrics for comparison between samples but rarely produce absolute values as they lack in robust standards and statistically relevant data (moreover so for interfacial CMC properties).29

The most accurate method for determining the properties at the micro-scale remains the push-out and push-in methods on singular fibers. The very first fiber push-outs were theorized by Marshall in 1985 and performed in 1987 by Marshall

![FIGURE 1 Adhesive (left) and cohesive (right) failures as CMC interfacial failure mechanisms][Color figure can be viewed at wileyonlinelibrary.com]
The interfacial shear stress $\tau$ experienced at the interphase can be estimated by:

$$\tau = \frac{F}{2\pi R H}$$

where $F$ is the push-out load in mN, $R$ is the fiber radius in microns, and $H$ is the sample thickness in microns.

The equation can be derived from the generic force balance:

$$\sigma_0 \pi r^2 = \tau_0 L 2\pi r$$

The use of nanoindentation is ideal for fiber push-out when the tip is flat, preventing fiber decohesion or breakage. A flatter tip will also decrease the amount of material that is wedged over as surplus from the surface of what is being indented. Such tests have been performed in the literature but fail to consider all the experimental parameters highlighted below.

### 1.1 Sample thickness

The thickness of the samples needed for push-out has been an ongoing problem in the micromechanical community. Thicker samples will likely experience exaggerated shear stresses at the interface due to fiber/matrix elastic incompatibilities, enhanced effects of the load train/instrument compliance (although Mueller argued that there is little to no effect from the sample flexural stiffness on shear measurements), or increasing number of protruding fibers after sample preparation (cutting) as both stresses relax and interphases degrade. The polishing was also speculated to further introduce in-plane compressive stresses. At 100 µm thicknesses, the weave dimensions are reduced to single tow thicknesses which removes the composite geometry variable in calculating absolute values; however, this can sometimes induce problems during sample preparation as others have reported fiber tows unsheathing from their surrounding matrix during polishing as a result of residual compressive stresses relaxing. Rebillat further showed that fibers could not be pushed out more than 10 times their diameter size (which is roughly from 10 to 15 µm for third-generation fibers) as wear effects start being too significant. Novel Solutions to sample thinning include the argon ion slicing process highlighted by Herbreteau and the wedge shape preparation by Wing.

### 1.2 Residual stresses in the matrix

A Poisson phenomenon and a differential thermal contraction (from the difference in coefficient of thermal expansion during manufacture) also cause the fiber to expand during push-out, which induces (rather than offsets) radial compressive stresses across the interface. The Poisson effect converts axial stresses into radial ones and is complex to quantify as it occurs contiguously with residual axial stresses from the lattice mismatch between interphase and fiber. Additional interfacial compressive stresses should also be considered during the push-out interfacial asperities from processing subsist as these will inhibit the fiber from sliding.

### 1.3 Tip positioning and tip radius

Kabel highlighted the fact that poor calibration of the microscope to indenter positioning can result in lower test throughput and data yield as the experimental acquisition is slowed down. The importance of indenter positioning with respect to the fiber cross-section was highlighted before in Desaeger’s work where any indent/push-out performed at an $r_i/r_f$ greater than 0.3 was discarded ($r_i$ being the distance between indenter center and the fiber center, and $r_f$ being the fiber radius). This was also demonstrated in a model by Rodríguez showing that push-in behaviour is independent of flat punch tip radius provided a $r_i/r_f$ ratio exceeding 0.6 is maintained. This effect is further accentuated when Berkovitch tips are used as fiber cracking is more easily induced with misalignment to fiber center.

### 1.4 Debonding location (interphase-scale)

Debonding at the BN interlayer scale is more favorable if a crack propagates between the matrix and the interlayer, rather than the interlayer with the fibers. These mechanisms are termed “outside” and “inside” debonding, respectively, with the latter giving reduced stress-oxidation capabilities of the composite and shorter pull-out lengths. Outside debonding was found to induce much longer push-out lengths and weaker interfacial shear strength (~10 MPa) when compared to inside debonding (~70 MPa). Other changes in the composite microstructure such as interphase thickness or doping of the BN interphase result in tendencies to favor “outside” debonding.

### 1.5 Fiber local environment (intra-tow variability)

The BN interphase coating a fiber preferentially oxidizes when neighboring another fiber as shown by the Opila group—as the SiC acts as an oxygen getter. The analysis of neighboring fibers and local fiber environment is a clear gap of knowledge in the community as previous fiber
Recent research has begun investigating the effect of local fiber environment including Molina-Aldareguía et al., Rodríguez et al., and Xu et al., who purposely pushed fibers in if they possessed hexagonal neighboring symmetries (termed “highly packed fiber clusters”) showing that the fiber local environment had a significantly large effect of data scatter. Rodríguez et al. further showed that experimentally and when modeling, only the closest proximity of the fiber (i.e., only one further fiber away) should be taken into account and therefore a fiber with a sixfold hexagonal neighboring symmetry is not influenced by the matrix stresses or plastic deformation. Furthermore, pushing out fibers in the middle or at the edge of tows influences results as the number of fibers surrounding the tested fiber has an influence on radial and axial stresses. Similarly, variations in interfacial shear stresses found in fibers of similar environments may be due to the variations in thermal residual stresses between the BN coating and the fiber from processing.

1.6 Tow environment (inter-tow variability)

Variations in inter-tow mechanical properties as opposed to intra-tow variations were investigated by Zok et al. who found no direct correlation between testing fibers close (1 mm) or from a distance (10 mm) to the fracture plane, as well as no evidence of fibers locking (from interphase debris or other fibers) during testing. However, there exists a difference in coating thickness (for both BN and SiC) deposited by CVI proportional to the distance of the tow to the outskirts of the CMC—thus potentially influencing the interfacial measurements.

1.7 Statistical studies

Most studies on fiber push-outs are conducted on a very small number of fiber push-outs, thus limiting the understanding and analysis/interpolation of the results obtained, and further not taking into account the influence of parameters highlighted in points A–F. The significance of the number of tests needed for acquisition of a representative population is further discussed.

1.8 Questions to address

Several questions stem from this review on the experimental limitations of the fiber push-out technique—some of which were addressed in the past but lacking in statistical robustness which will be addressed in this work:

- How does the fiber local (intra-tow) and tow-level (inter-tow) environments affect the variability of our interfacial properties measurements?
- Does the type of failure (adhesive or cohesive) dominating change as a function of interphase thickness?
- How does the thickness of the sample affect the push-out success rate experimentally and how can the “exaggerated shear stresses” at the interface be measured should the sample thickness exceed 100 µm?
- Fiber push-outs are commonly performed with a flat-punch tip, however how does the radius of this tip affect measurements?

This then leads us to consider the experimental data from a stochastic point of view; how can one optimize measuring an accurate value for the interfacial shear strength of the interlayer?

2 EXPERIMENTAL PROCEDURE

2.1 Materials

The SiC/BN/SiC in this study has either a thin (~200 nm), medium (~400 nm), or a thick (~600 nm) BN CVD (Chemical Vapor Deposition) interphase coating on the fibers. The fibers themselves are third-generation fibers either Hi-Nicalon™ type S (from COI Ceramics Inc.) or Tyranno SA grade 3 ® (from Ube Industries Ltd.). The fiber tows are woven into a balanced 2D 5HS woven fabric and stacked to form a preform that is then coated with a CVD BN and a subsequent densification with CVI (Chemical Vapor Infiltration) SiC. These porous preforms are then densified with SiC slurry and finally a Si melt infiltration. The three samples used in this study have generic dimensions highlighted in Table 1 and a typical microstructure pictured in Figure 2(D).

2.2 Basics of fiber push-out

Sample preparation for fiber push-out is crucial as slight variations in samples will induce significant changes in measurements of the micro-scale properties. Samples were first cut and ground using oil-based diamond solutions to avoid BN environmental degradation from reactions with water forming Boria glass. Samples were mounted on a custom-built holder for grinding to a specific 100 µm thickness with an accuracy of ±10 µm. Samples were ground, polished down to 1/10th µm diamond paste size, and cleaned with propan-2-ol in between steps. Polishing quality was verified via means of optical microscopy—fibers ideally presented as completely rounded with no damage, damaged samples were either discarded or
Sample cleaning post-polishing included 1 acetone bath (10 min) and 2 ethanol baths (5 min each) in ultrasonic environment. Samples were then flipped and polished on the reverse side for pushed-out fibers to be clearly visible. No damage to the BN layer was observed in this process.

Once polished on both sides, samples were subsequently mounted with minimal amounts of Quickstick 135°C Mounting Wax from South Bay Technology on a custom-build holder with 1-mm wide slits for fibers to be pushed into while supporting the sample to prevent macroscopic bending. The holder was mounted in a G200 Nanoindenter (Agilent, USA) instrument before testing.

Push-outs were performed at a prescribed displacement rate of 30 nm.s⁻¹ to a maximum 3 μm displacement to avoid the conical-shaped flat-punch tip hitting the matrix at the edge of the fiber. The tips used were 3, 5, and 7 μm in diameter. Samples were not cleaned after fiber push-outs to prevent tested fibers from damage or falling out. Samples were subsequently analyzed under SEM with images taken at a working distance of 10.5 mm and accelerating voltage of 10 keV and a probe size of 800 pA, using a vertical sample holder to measure sample cross-sectional thickness as seen in Figure 2(C), fiber diameters, and push-out lengths (accounting for sample tilt corrections) for each successful push-out. The success of a fiber push-out was defined as a test having a clear plateaued load curve and no visible fiber breakage (and a visible fiber pushed on the bottom edge of the test). Due to the plastic deformation induced by the tip on the fiber itself, the first 400 nm ± 61 nm displacements were omitted before calculating interfacial shear stresses—this depth was double that found by Medina et al. Only plateaued load curves (showing load bursts attributed to full crack propagation and fiber sliding) were therefore used for data analysis. The thickness, fiber diameters, and load/displacement values were used to calculate a simple force-balance-derived interfacial shear stress τ from Equation 1. Due to the stochastic nature of fiber push-outs, all push-out data are presented probabilistically using cumulative frequencies to yield best-case and worse-case design scenarios for performance envelope libraries. These cumulative distribution functions enable comparisons between samples—the ISS is, ranked, binned in 2 MPa increments, and counted before plotted against normalized frequency.

## 2.3 Effect of sample thickness on sample preparation

To explore how the thickness of the overall sample affected batch push-outs, the success rate of 100 fiber push-outs on
each of four samples of the same fiber type (Hi-Nicalon type S) and BN thickness (600 nm) was plotted against measured sample thickness (Figure 4). The samples were ground to respective thicknesses of 83, 167, 200, and 287 µm.

2.4 | Effect of tip size

To investigate the effect of tip size on both the ISS and push-out success rates, 100 push-outs were repeated using a 3 µm and a 7 µm diameter tips on the same sample made with Tyranno type SA3 fibers and a thin BN interphase.

2.5 | Effect of thickness of BN interlayer

The effects of fiber type (Tyranno type SA3/Hi-Nicalon type S) and interphase thickness (200/600 nm) were investigated. At least 200 push-outs were performed on each of the three samples highlighted in Section 2.1. Half of the push-outs were performed at the edge/periphery of a tow while the other half performed in the center of tows as illustrated on Figure 3 to concurrently investigate the effect highlighted in Section 2.4.

2.6 | Effect of fiber location inside sample

The heterogeneity in load/displacement behaviour of push-outs could have partially been due to the difference in local fiber environment—as some are present inside tows surrounded by other fibers while others are segregated in the matrix (at tow periphery) and surrounded by all CVI SiC. More fiber push-outs on a single sample (Tyranno type SA3 with thick BN) were therefore performed to look at the performance of the interlayer inside and at the periphery of a fiber tow highlighted in Figure 3. As fibers have a differing number of neighbors, this might influence the strength of the interlayer being pushed out.

3 | RESULTS

3.1 | Effect of sample thickness on push-out success rate

A decreasing trend is observed in Figure 4 where the push-out success rate reaches 100% when the sample thickness decreases below 100 µm. Factors other than the load limit on the indenter head are laid out in the discussion below.

3.2 | Effect of tip size

A few observations stemmed from push-outs completed using different sized tips on the same sample. First, it was observed that Tyranno type SA3 fibers were more prone to cracking (Figure 5(C)) compared to Hi-Nicalon type S when indented with the same flat-punch tip—this may have resulted from either the slightly smaller average diameters of the Tyranno fibers or the higher density of secondary carbon deposits (and therefore crack initiation sites density) in the middle of the Tyranno type SA3 fibers. Comparing the ISS cumulative frequencies on Figure 5(A) and (B), it was found that the 3-µm tip ISS was on average greater than those from the 7 µm counterpart. The push-out success rate was higher with the 3 µm tip despite the majority of the fibers breaking due to the high stress intensity factor located at the sharper nanoindenter tip. Conversely, push-outs completed with the 7 µm displayed lower success rates and were also harder to calibrate in terms of lateral stage positioning as indents created prior to fiber push-outs were less distinctive and shallower than the 3 µm tip. Using a larger tip such as the 7 µm
tip on fibers with an average diameter of 10 μm also significantly increased the chances of the tip indenting the BN interphase at the edge of the fibers. For Tyranno type SA3 and Hi-Nicalon type S fibers, it is therefore recommended that a ratio of 1:2 is maintained for tip/fiber numerical average diameters.

### 3.3 Fiber push-out: effect of thickness of BN interlayer

Figure 6 plots the cumulative distribution functions of the ISS obtained when testing in fiber push-out. Comparing fiber types in the first instance, Tyranno type SA3 sample (in red on Figure 6), seems to have the highest interfacial shear stresses with a mean and median of 50.6 and 48.5 MPa, respectively, as summarized in Table 2. The thickness of the BN interlayer has a significant effect on the distribution of the ISS with respect to fiber location within a tow—indeed, fibers pushed on the sample with the thinner interlayer (in grey on Figure 6) displayed no bias with respect to fibers pushed at the periphery or in the middle of tows (this is further investigated in the discussion). When looking at the effect of the thickness of the interphase and comparing the Hi-Nicalon type S samples with a thin (grey) and a thick (blue) BN layer, it is clear that in the lower end of the ISS spectrum, fibers are harder to push-out if only a thin BN is coating the fiber. This is reflected in the values in Table 2 where all mean and median values for the thin interphase (columns 2 and 3) are greater than the respective values of the thicker interphase (columns 4 and 5); therefore, a thinner interlayer resulted in higher shear stresses.
3.4 Effect of fiber location inside sample

Push-outs were completed in batches at different locations within the Tyranno type SA3 with thick BN sample to investigate the effect of fiber local environment on the ISS measured as illustrated in Figure 3.

First, push-outs—of random location within a tow—were completed in different fiber tows on Figure 7(B). Push-outs completed in tows at the edge of the sample as illustrated in Figure 3 (with thicker CVI SiC interlayers surrounding the tows) were found to be statistically easier to push-out (lower mean and median ISS of 33.2 and 31.7 MPa, respectively) and then fibers pushed out in tows close to the center of the sample (with a mean and median ISS of 39.0 and 36.1 MPa respectively); however, as the cumulative distributions overlap, the statistical significance of this result is ambiguous (further analyzed below).

Second, it was found that for samples with a thick BN interphase, fibers at the edge of a tow were statistically harder to push-out than fibers in the center of tows (surrounded by numerous neighboring fibers—up to 6 in a hexagonal stacking configuration—and therefore with more shared interphase contact area) as shown more clearly (no overlap of the cumulative distribution functions) in Figure 7(A).

Performing an unequal variance two-tail t-test (with $\alpha = 0.05$ and a hypothesized mean difference of 0) comparing intra-tow (Figure 7(A)) and inter-tow (Figure 7(B)) populations, we find that the t stat for the intra-tow populations (2.73) sits above the positive t critical for two-tailed analysis (2.03), and that the t stat for the inter-tow populations (−2.27) sits below the negative t critical for two-tailed analysis (−1.98); both of which confirm the hypothesis that the populations share the same mean can be rejected. This is also reflected in the $p$ values obtained (two-tailed) of .009 (intra-tow) and .025 (inter-tow) both being lower than $\alpha$, reinstating that in both cases (intra-tow or inter-tow), all populations are significantly different.

This was further investigated using “cascade” push-outs on a sample with Tyranno type SA3 fibers with a medium-sized BN interphase. Several fibers were pushed out around a target fiber which was subsequently pushed out—for example in Figure 8 the central fiber was pushed out after its first three neighbors (left) or five to six neighbors (right).

The ISS measured was also plotted (Figure 9(A)) as function of the undamaged “leftover” BN surface area coating the fiber. This area assumes a perfectly cylindrical fiber and a minimum of 2 $\mu$m in cross-sectional arc length of contact length (BN interlayer) connecting two fibers. The ISS

| Sample         | HNS – thin BN | HNS – thick BN | TSA3 – thick BN |
|----------------|---------------|----------------|-----------------|
| Location       | Tow edge      | Tow middle     | Tow edge        | Tow middle     | Tow edge | Tow middle |
| Mean           | 31.9          | 32.6           | 24.1            | 11.9           | 50.6     | 35.5      |
| Standard deviation | ±7.0         | ±5.0           | ±17.5           | ±7.0           | ±10.0    | ±15.0     |
| Median         | 33.7          | 32.2           | 15.6            | 6.4            | 48.5     | 39.9      |
| 1st Quartile   | 27.7          | 28.8           | 9.2             | 4.0            | 44.5     | 25.6      |
| 3rd quartile   | 37.2          | 37.3           | 39.7            | 10.9           | 60.9     | 46.1      |

Bold: Mean and median values were mentioned in the article text, the bold font serves to highlight those values.
increases as more BN is left pristine (Figure 9(A)). Plotting the ISS as a function of the area metric enabled direct correlation between the surface area/the theoretical amount of BN deformed and the measured interfacial shear stress.

4 | DISCUSSION

First, it was found that the overall thickness of the sample (Figure 4) affected success rate. Thicker samples will indeed likely experience exaggerated shear stresses at the interface due to fiber/matrix elastic incompatibilities as also highlighted by Desaeger et al.31 and increased risk of fiber misalignment/termination. No fiber unsheathing and protrusion was observed after or before polishing unlike Rollin et al.33; however, considering the thickness with near-perfect success rate was close to 10 times the fiber diameter, our observations are consistent with Rebillat22 and show there is a sample thickness/fiber diameter ratio to adhere to for optimized measurements of the ISS.

Results from Section 3.3 investigating the effect of interphase thickness compared a Hi-Nicalon type S sample with both thin and thick BN interlayers in Figure 6 and found that the thickness of the BN influences either the amount of (compressive) load sharing from the matrix to the fiber (previously shown by Wing et al.45 to be significant in SiC/SiC composites) and/or the work required to fully propagate the crack at the interphase. A thinner interlayer resulted in higher shear stresses due the higher possiblity of the interlayer being damaged along the fiber, as thinner interlayers may have had shorter deposition times and therefore lower chances of homogenously coating the fiber. Thinner interphases further accentuate the effect of fiber nano-asperities from surface roughness (in thicker interphases this effect is reduced). This argument can be extended to sample thickness whereby longer lengths of the fiber (and coating) might result in an increased likelihood of sampling the defects. The argument can be refuted by assuming that thicker interphases have a higher probability of containing a critical defect for a given load. The distribution of ISS values (Figure 7) in the lower end of magnitudes for inter-tow comparisons was narrower. This was most probably due to the smaller influence of fiber tapering, tilting, and offset, as well as the influence of the fiber volume fraction and eccentricity when testing tows on the outskirts of the sample. Figure 6 also showed no distinction between pushing fibers at the edge or in the middle of tows in samples with a thinner interphase (as opposed to those with a thicker interphase where the difference was more noticeable), suggesting there is a threshold interphase thickness which neutralizes the effects of fiber location within a tow. Thinner interphases may result in more inherent defects and a higher probability of the interlayer not coating the fiber fully from manufacturing before the fiber push-out begins—thus influencing push-outs and resulting in little difference between pushing a fiber with a thin interphase and no interphase at all.

“Cascade” push-outs on a sample with a medium-sized BN interphase in Figure 8 helped support this hypothesis when damaging the BN connecting 2 neighbors showed strong correlation with the ease at which a fiber can be pushed out. Indeed, pushing a fiber neighboring one which
3. A ratio of 1:2 for the tip:fiber diameter was found to optimise flat-punch tip push-outs as a higher ratio resulted in increased chances of indenting neighboring fibers/environment and a lower ratio resulted in increased stress intensity factor at the tip edges rendering the fiber more prone to cracking.

4. Models taking into account fiber environment should place more emphasis on intra-tows variations than inter-tows variations.

5. A correlation was found between the interfacial shear strength measured on a fiber with respect to the number of neighbors pushed out around the central fiber. This correlation could be fitted and/or used for modeling purposes.

6. The thickness of the BN interlayer in these SiC/SiC composites has a significant effect on the distribution of the ISS with respect to fiber location within a tow:
   a. for thinner BN interlayers, the location of the fiber within the tow (at its periphery or in the middle) has no effect on the cumulative frequency of the Interfacial Shear Strength found
   b. for thicker BN interlayers, fibers pushed at the periphery of tows were significantly harder to push-out on statistical average when compared to fibers pushed in the middle of tows.

**ACKNOWLEDGMENT**

The authors would like to thank Rolls-Royce plc for supplying the composite materials studied in this work and for providing funding for the project. The authors acknowledge the use of characterization facilities within the David Cockayne Centre for Electron Microscopy, Department of Materials, University of Oxford, alongside financial support provided by the Henry Royce Institute (Grant ref EP/R010145/1).

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How to cite this article: De Meyere RM, Gale L, Harris S, Edmonds IM, Marrow TJ, Armstrong DE. Optimizing the fiber push-out method to evaluate interfacial failure in SiC/BN/SiC ceramic matrix composites. J Am Ceram Soc. 2021;104:2741–2752. https://doi.org/10.1111/jace.17673