THE ELECTRICAL CONDUCTIVITY OF SiC_f/SiC – EFFECTS OF PYROCARBON FIBER COATING THICKNESS AND CONTACT RESISTANCE – G. E. Youngblood and E. Thomsen (Pacific Northwest National Laboratory)* and R. J. Shinavski (Hyper-Therm HTC, Inc.)

OBJECTIVE

The primary objectives of this task are: (1) to assess the properties and behavior of SiC_f/SiC composites made from SiC fibers (with various SiC-type matrices, fiber coatings and architectures) before and after irradiation, and (2) to develop analytic models that describe these properties as a function of temperature and dose as well as composite architecture. Recent efforts have focused on examining the electrical conductivity properties of SiC_f/SiC composites considered for application in FCI-structures in support of the U.S. dual-coolant lead-lithium (DCLL) fusion reactor blanket concept.

SUMMARY

The previous report examined in-plane and transverse electrical conductivity (EC) data from RT to 800°C for several forms of two-dimensional silicon carbide composites made with a chemical vapor infiltration (CVI) matrix (2D-SiC/CVI-SiC). A fairly substantial correction due to contact resistance at the sample-electrode interface was required to arrive at transverse EC-values, an important quantity needed for the design of a flow channel insert (FCI). In this report, the dependence of in-plane and transverse EC-values for 2D-SiC/CVI-SiC on the total thickness of the pyrocarbon (PyC) fiber coating is examined. As previously hypothesized, both in-plane and transverse EC-values for 2D-SiC/CVI-SiC strongly depend on the total thickness of the PyC fiber coating, and the interconnectivity and alignment of the carbon-coated fiber network. Our "3-layer series" model predicts that transverse EC-values for a seal-coated 2D-SiC/CVI-SiC with a monolayer PyC fiber coating of ~50 nm thickness will be <20 S/m for all temperatures up to ~800ºC, as desired for the FCI-application.

PROGRESS AND STATUS

Introduction

New EC data for 2D-SiC/CVI-SiC made with Nicalon™ Type S 0/90 woven fabric coated with a relatively thin ~50 nm monolayer of pyrocarbon (PyC) are reported. These data are analyzed together with the previously reported results for a similar composite prepared with multi-layer PyC/SiC fiber coating with a thicker ~200 nm total PyC thickness. All of these experimental results were acquired in support of a DOE-sponsored SBIR contract (DE-FG02-07ER84717) with Hyper-Therm HTC, Inc. The EC measurement systems and protocol as well as the previous results for 2D-SiC/CVI-SiC composite, and for dense, monolithic CVD-SiC are described in Fusion Material Semiannual Progress Reports (FMSPR) [1-5].

In FMSPR [4], a simple model was introduced that describe's the transverse EC(T) of a 2D-SiC/CVI-SiC plate in terms of the EC of the interior, carbon net-worked SiC fabric-layered region in series with outer "seal coat" layers of densely adherent, single phase CVD-SiC (in our case). The transverse EC(T) for such a three-layered composite can be expressed by:

$$EC(T) = EC_{int}[1 - 2f(1 - R)]^{-1} \qquad [1]$$

In Eq. [1], T is temperature, f = t/L where t is the average thickness of a seal coat layer, L is the composite plate thickness (including the seal coat layers) and EC_{int} is the transverse EC for only the interior region of a 2D-SiC/CVI-SiC. EC_{int} was determined by making EC measurements on a disc sample with each surface ground down well into the fabric layer region. Also, R is the ratio EC_{int}/EC_{sc}, where EC_{sc} was

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calculated for a CVD-SiC seal coat of known thickness using values of EC measured for representative samples of pure, monolithic CVD-SiC [2]. Note that EC(T) is NOT an intrinsic property of 2D-SiC/SiC, but rather an "effective" transverse electrical conductivity useful for comparing designs for FCI-structures subject to potentially a deleterious MHD pressure drop in a DCLL blanket.

As previously shown, electrical conduction in the interior region of a high quality 2D-SiC/SiC composite with carbon-coated fibers is dominated by the amount of high conductivity carbon, even though the amount of carbon is only a few percent. Importantly, the continuity of the fiber coatings with parallel alignment control the in-plane EC, while the amount or lack of interconnectivity of the carbon fiber coating network through touching fiber coatings is important in determining the conduction in the transverse direction of a 2D-composite [5].

When using a simple 2-probe measurement method (no guard ring attachments), which is preferred when measuring the transverse EC and its temperature dependence of a relatively thin disc-shaped sample, the measured EC(T)-values must be corrected for contact resistance. This is not trivial as the contact resistance is very dependent on sample surface preparation and type of electrodes used as well temperature. Usually the contact resistance at the interior region/electrode interface is much less than that at the pure SiC seal coat/electrode interface. The interior region/electrode contact resistance is less because numerous, highly conductive carbon coating pathways penetrate this interface and make direct electrical contact with the metal electrodes. Nevertheless, the current density at the electrode-interior region interface is far from uniform; there will always be at least some contact resistance due to current constrictions at this interface. Thus, the actual contact resistance will depend upon the carbon network configuration as well as the number of carbon-electrode contacts at the interface. At lower temperatures, SiC acts more like an electrical insulator (actually SiC is a wide band gap semi-conductor and exhibits a relatively steep temperature dependence) and the contact resistance for a SiC-metal contact may become very large. At higher temperatures, SiC becomes more conducting; the electrical current is more uniformly spread across a SiC-metal interface and contact resistance decreases dramatically. This is the reason that the preferred method to estimate the transverse EC(T)-values for 2D-SiC/CVI-SiC with a SiC seal coat is to measure $EC_{int}(T)$ directly with a 2-probe method that at least minimizes contact resistance, and then calculate EC(T) using Eq. [1].

In this report the specific contact resistance as function of temperature will be estimated for three types of electrodes (Au and thin and thick layers of porous Ni) applied to 2D-SiC/CVI-SiC with the same weave patterns but different carbon fiber coating thicknesses. Then, using Eq. [1] our 2-probe $EC_{int}(T)$-data will be used to obtain an estimate of the transverse EC(T) for 2D-SiC/CVI-SiC with a relatively thin CVD-SiC seal coat for each case.

Experimental Procedure and Results

Two bar and two disc samples of 2D-SiC/CVI-SiC with 8HS-0/90 weave (referred to as Batch 3 samples) and with a monolayer carbon fiber coating of purposely-reduced thickness were obtained from Hyper-Therm, HTC. Except for the fiber-coating step, these new samples were produced in the same manner as the samples with thicker, multilayer (ml) PyC/SiC fiber coatings examined in the previous report (Batch 1 and 2 samples) [5]. As before, bar samples (40 x 5.3 x 3.1 mm) were used for 4-probe in-plane EC measurements; disc samples (10 mm diameter x ~2 mm thick.) were used for measurements normal to the plane of the woven SiC fabric layers, i.e., the transverse direction. Measurements were made as a function of temperature during a heating-cooling cycle up to ~800ºC in ~40ºC steps. The EC of disc samples was measured first for as-received samples with the SiC seal coat intact, then again after the SiC seal coat was removed. For the latter case, ~0.1 mm was ground from each disc surface to expose a surface cut well into the carbon net-worked interior region. The disc faces were polished before reapplying the electrodes; however it was difficult to prepare an undamaged in-plane surface. The small diameter SiC fibers lying parallel and exposed near the cut surface sometimes broke and dislodged during polishing. Porous nickel electrodes (reduced NiO) were used for all disc sample EC-measurements except for the 2D-GE sample, where evaporated gold was used [5].

Because our main concern in this report is the effect of the thickness and configuration of the carbon fiber coating on both the specific contact resistance and EC(T), only representative samples from the previous report with 0/90 weave orientation are considered here. Therefore, in Tables 1-2 sample codes, batch designation, weave-type, carbon layer thickness(es) as well as the individual sample bulk density values are listed only for the Hyper-Therm fabricated bar and disc samples selected for this study, respectively. A bar and a disc reference sample of 2D-SiC/CVI-SiC made by General Electric with a ~150-nm monolayer PyC fiber coating also are listed [5].

Table 1. Bar Samples (4-probe in-plane EC)

Code	Type	thickness PyC (nm)	Bulk Density (g/cc)
B1	Batch 1, 5HS weave	180 + 4(20), C/SiC ml	2.77
B2	" " "	" "	2.78
B7	Batch 2, 8HS weave	230 + 4(20), C/SiC ml	2.75
B9	" " "	" "	2.85
B17	Batch 3, 8HS weave	50, monolayer	2.80
B18	" " "	"	2.73
2D-GE	Ref., 5HS weave	150, monolayer	2.69

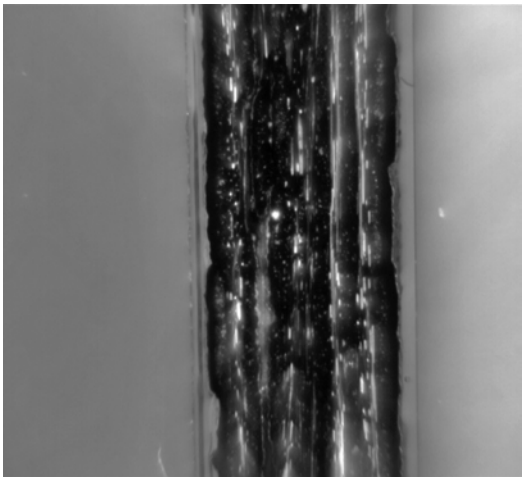
Table 2. Disc Samples (2-probe transverse EC)

Code	Type	thickness PyC (nm)	Bulk Density (g/cc)
D1	Batch 1, 5HS weave	180 + 4(20), C/SiC ml	2.71
D8	Batch 2, 8HS weave	230 + 4(20), C/SiC ml	2.79
D12	Batch 3, 8HS weave	50, monolayer	2.73
2D-GE	Ref., 5HS weave	150, monolayer	2.69

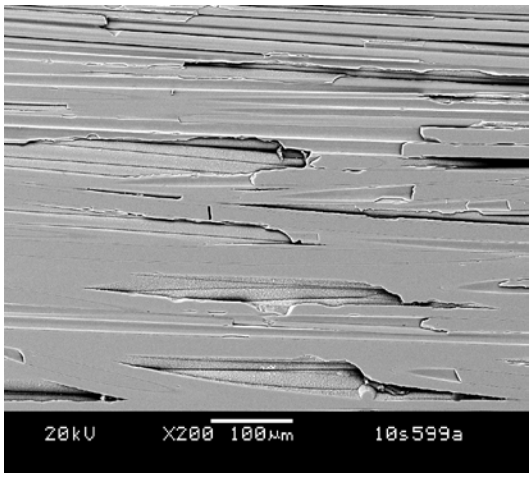
In Figures 1(a-d), an optical micrograph of a polished transverse cross-section of the Hyper-Therm 2D-SiC/CVI-SiC composite with 50-nm monolayer PyC fiber coatings shows the general spacing of the fabric-layered interior region and the adherent, ~50µm thick outer SiC seal coat layers (1a); and SEM views that show details of a damaged polished surface cut into the interior fabric-layered region (1b) and the continuous PyC interconnectivity along individual fibers or an intermittent PyC interconnectivity between neighboring fibers within the yarn bundles (1c) or between neighboring fibers (1d). In particular, (1b) shows that a serious amount of surface damage occurred to the surface cut into the fabric-layered interior region even though extreme care was taken during final polishing. When the SiC matrix covering an in-plane fibers became too thin it sometimes broke away from the underlying fiber. Nevertheless, a number of direct Ni metal-PyC fiber coating contacts occurred at such an interface.

In Figure 2, the in-plane EC(T)-values from RT to ~800°C measured using the 4-probe method for the bar samples listed in Table 1 are given. The slight deviation from a smooth curve observed for sample discs B7 and B9 is thought to be an artifact due to the automated data acquisition system. Also, the cooling legs of each 800°C temperature cycle were reproducible with the heating legs for all of the samples, so for clarity only the values determined for the decreasing temperature leg are presented here.

In Figure 3, the measured electrical resistance values, R(T), in the transverse direction for the disc samples listed in Table 2 with and without SiC seal coat are given. For each disc sample, the two curves represent total resistances (including contact resistances) across the samples with the SiC seal coat intact (dashed) and with the seal coat removed (solid).



1(a) ---------- 1 mm



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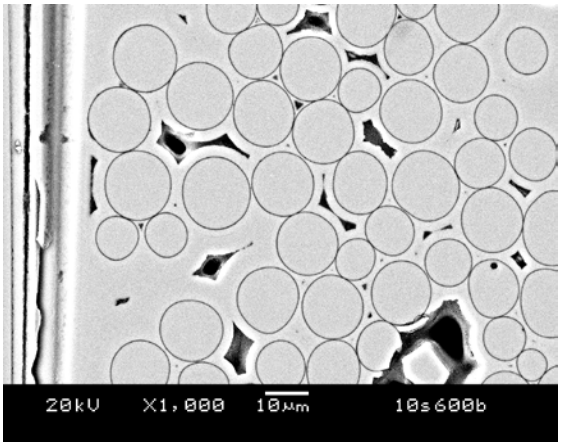
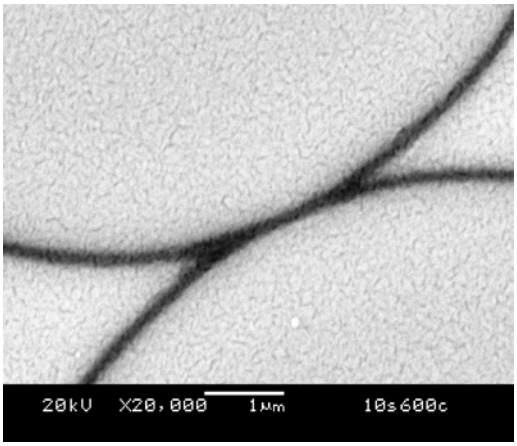


1(c)



1(d)

Figure 1(a-d). An optical micrograph of a polished transverse cross-section of the Hyper-Therm 2D-SiC/CVI-SiC composite with the thin monolayer PyC fiber coatings that shows the general spacing of the fabric-layered interior region and the adherent SiC seal coat layers (a); and SEM views that show details of a damaged polished surface cut into the interior fabric-layered region (b) and the continuous PyC interconnectivity along individual fibers or intermittent PyC interconnectivity between neighboring fibers within the yarn bundles (c) or between neighboring fibers (d). Backscatter electrons were used for the SEM views, so the carbon layers are dark and a little fuzzy. The CVI-SiC matrix and fiber components (Nicalon™ type S fiber is ~99% polycrystalline SiC) appear light grey.

In Figure 2, the in-plane EC(T)-values from RT to ~800°C measured using the 4-probe method for the bar samples listed in Table 1 are given. The slight deviation from a smooth curve observed for sample discs B7 and B9 is thought to be an artifact due to the automated data acquisition system. Also, the cooling legs of each 800°C temperature cycle were reproducible with the heating legs for all of the samples, so for clarity only the values determined for the decreasing temperature leg are presented here.

In Figure 3, the measured electrical resistance values, R(T), in the transverse direction for the disc samples listed in Table 2 with and without SiC seal coat are given. For each disc sample, the two curves

represent total resistances (including contact resistances) across the samples with the SiC seal coat intact (dashed) and with the seal coat removed (solid).

Analysis and discussion

The in-plane EC(T)-data in Fig. 2 appear to exhibit three general features: (1) the in-plane EC-value curves all lie roughly parallel to each other and exhibit a similar temperature dependence with the EC-values gradually increasing as temperature increases; (2) the in-plane EC-values for each pair of bar samples with the same PyC fiber coating total thickness were reproducible within a few percent; and (3) a marked decrease in EC-values occurred as the PyC fiber coating thickness decreased from 310 nm down to 50 nm (at RT, ~800 S/m for 310-nm PyC, 450 S/m for 260-nm PyC, 325 S/m for 150-nm PyC, and 150 S/m for 50-nm PyC, respectively). The in-plane EC(T)-values for all the bar samples were higher than observed for monolithic CVD-SiC (see Fig. 5), and exhibited a much shallower temperature dependence than CVD-SiC (~100 S/m at 800ºC down to 1 S/m at RT). As previously hypothesized [5], the in-plane EC(T) for 2D-SiC/CVI-SiC primarily depends on the thickness of the relatively continuous, high conductivity PyC coatings on the fiber bundles aligned parallel to the conduction direction even though the amount of carbon is only a few percent, and not so much on the electrical conductivity of the CVI-SiC matrix.

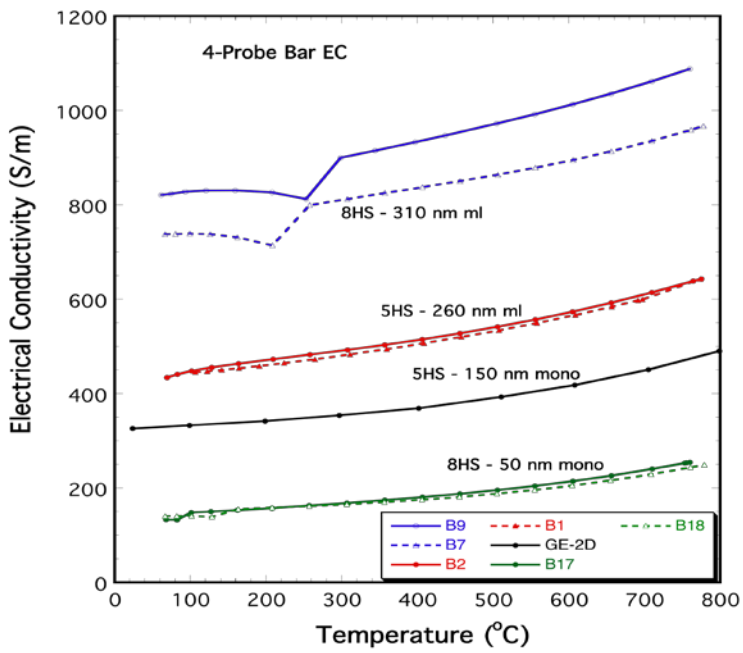


Figure 2. In-plane EC(T)-values for representative 2D-SiC/CVI-SiC bar samples (see Table 1) with 0/90 weave. The total PyC thicknesses for each grouping were 310 nm (multilayer), 260 nm (multilayer), 150 nm (monolayer), and 50 nm (monolayer), in descending order. A 4-probe dc method was used.

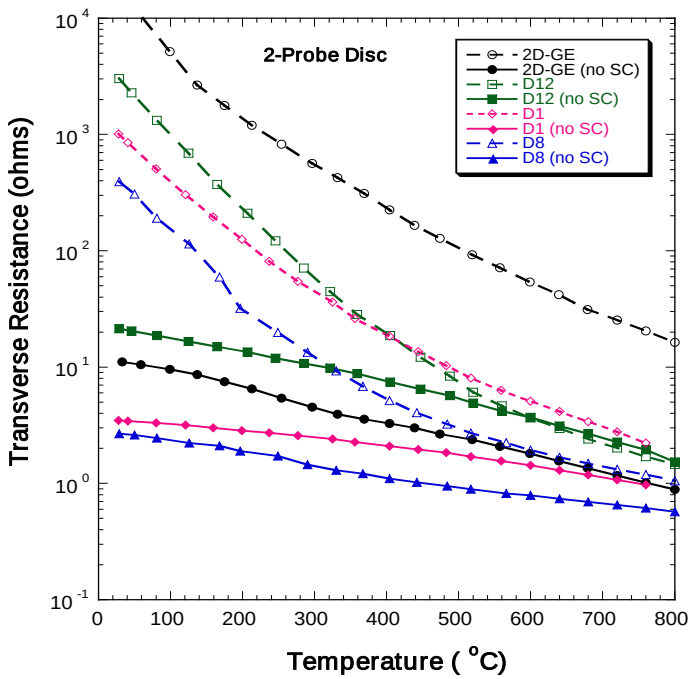


Figure 3. Transverse electrical resistance values as a function of temperature for the 2D-SiC/CVI-SiC disc samples listed in Table 2 with the SiC seal coat intact (open symbols) and removed (closed symbols). A simple 2-probe dc method was used.

In Figure 3, at room temperature the absolute transverse electrical resistance values for the representative disc samples with different total PyC fiber coating thicknesses (see Table 2) and with their SiC seal coats intact (dashed lines, open symbols) were much higher than corresponding values for the same samples with their seal coats removed (solid lines, closed symbols). Also, the high values (~10^4 - 10^3 ohms) decreased dramatically with temperature increasing up to 800ºC until the resistance values were only slightly more than the values observed for the samples with seal coats removed (~1-10 ohms).

This difference is attributed to a large contact resistance, especially at lower temperatures, inherent when using a 2-probe dc measuring method. In our case, use of a 2-probe method is dictated by the small size of the disc samples used (~1 cm dia.) and the inhomogeneous nature of 2D-SiC/SiC made with stacked layers of woven fabric. A 4-probe method could not possibly be connected to measure uniform potential drops across such a thin, inhomogeneous disc-shaped sample. Because of the inhomogeneous nature of these samples, even a guarded ring method would be subject to the influence of non-uniform current distribution and contact resistance.

Apparently, grinding off the dense SiC seal coat into the fabric-layered interior region of the composite considerably reduced the contact resistance by exposing the carbon networked interior region. Then the applied porous Ni electrodes made good electrical contact through the exposed carbon network. Although the thin SiC seal coat itself contributes a small amount to this difference in resistance, most of the separation is due to contact resistance at the electrode-SiC interface. If the small contact resistance for the "no SC" case is ignored (estimated previously to be ~1 Ωcm^2), the contact resistance (R_c) can be estimated for resistances in series as

$$R_c \sim R_{tot} - R_{int} - 2r \qquad \text{q. [2]}$$

where R_{tot} and R_{int} are the measured resistances across a disc sample with seal coat intact or ground off, respectively; and r is the calculated resistance for the thin SiC seal coat layer on each disc.

We calculated r for a seal coat layer 50 microns thick when using EC(T)-values measured in our lab for high-purity CVD-SiC [3]. The specific R_c(T)-values (in Ωcm^2) estimated from Eq. [2] are shown in Fig. 4.

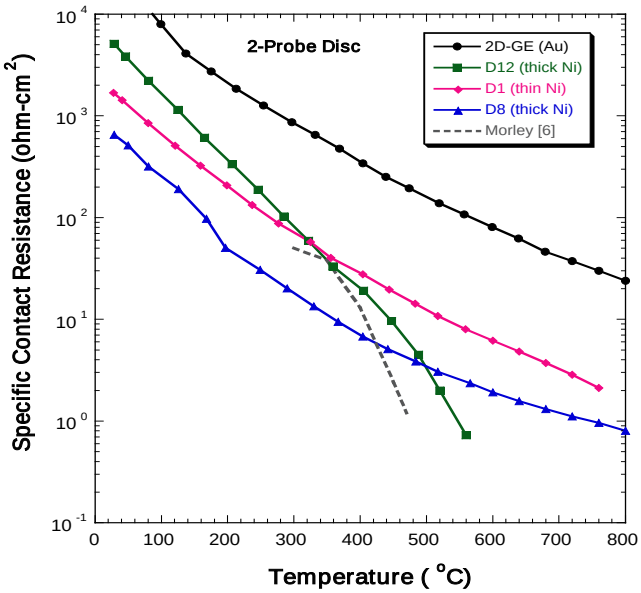


Figure 4. Estimated R_c(T) from Eq. [2] for 2D-SiC/SiC disc samples: 2D-GE (evaporated Au electrodes), D1 (thin porous Ni electrodes), and D8 and D12 (thick porous Ni electrodes). For comparison, the data from Morley [6] for a liquid Pb-Li electrode on monolithic CVD-SiC are shown in dashed gray.

In Figure 4, the specific R_c(T)-values decrease rapidly with increasing temperature from > 10^4 Ωcm^2 at RT to ~1-20 Ωcm^2 at 800°C. Also, the R_c-values depended sensitively on the type of electrodes used with values for the evaporated Au electrodes being significantly larger than those for porous Ni electrodes, and the values for thin porous Ni electrodes larger than those for thicker electrodes (except for sample D12, see below). Obviously, the contact resistance is large for samples with metal electrode-pure SiC interfaces, especially at low temperatures, and will seriously affect EC(T)-values when using a 2-probe method.

The specific R_c(T)-values depicted in Fig. 4 are subject to error, especially at lower temperatures, as the actual values for EC(T) for the SiC seal coat are not known. More importantly, at higher temperatures the contact resistance at the electrode-carbon networked interior region was ignored in Eq. [2]. Even though small it is possible that its absolute value is about the same magnitude as the sample resistance and should not be ignored. The latter situation appears to have occurred for disc sample D12 where the surface of the cut region was damaged due to pullouts during final polishing (see Fig. 1b), and likely accounts for the larger than expected R_c(T)-values observed at lower temperatures and the unusually steep downward sloping temperature dependence at higher temperatures. For this damaged surface condition, the number of actual direct contacts of the thin (~50 nm) PyC coating layers with the porous Ni electrodes likely were reduced, and a larger than normal contact resistance due to current restrictions at the electrode interfaces developed. For the disc samples with thicker PyC coating layers, the final

polished surfaces did not exhibit such extensive damage; the corresponding contact resistance values for the metal-carbon networked interior region likely were small enough so that Eq. [2] was valid.

Also, shown in Figure 4 are some estimated specific $R_c(T)$-values observed by Morley for 2-probe dc measurements on CVD-SiC with molten lead-lithium eutectic (LLE) electrodes, as would be the case for an operating FCI-structure [6]. Morley made measurements for three similar set-ups and observed significant contact resistances ranging from 1-100 Ωcm^2 when samples first came into contact with LLE near its melting point, the contact resistances decreased as the samples were further heated, and the resistances varied markedly from sample to sample, presumably depending on small variations in disc preparation. The magnitude of our values of $R_c(T)$ compare reasonably well with those values reported by Morley. Unlike Morley's observations with liquid metal electrodes, our $R_c(T)$-values for solid Au or porous Ni electrodes generally were reproducible with temperature cycling from RT-800ºC. Initially, we made measurements for three successive heating-cooling temperature cycles. We observed reproducibility of the EC(T)-values, so made measurements for a single temperature cycle thereafter. The reproducibility continued to be observed for each leg of the heating-cooling cycle. For the liquid Pb-Li metal electrodes, the contact resistance was time dependent; it likely depended on the degree of wetting with the SiC surface. For our porous Ni (or Au) electrodes, the contact resistance was time independent; it depended on the physical nature of a metal/semi-conductor interface as well as the quality of the SiC seal coat and its surface condition.

As stated earlier, the easiest way to obtain effective transverse EC(T)-values is to measure $EC_{int}(T)$ by a 2-probe dc method, hopefully with a minimum influence of contact resistance, and use Eq. [1]. In Figure 5, the estimated EC(T)-values from Eq. [1] (solid curves, closed symbols) are compared to the measured $EC_{int}(T)$-values (dashed curves, open symbols) for the four samples with different thicknesses of PyC fiber coating (D8 with 310-nm PyC, D1 with 260-nm PyC, 2D-GE with 150-nm PyC, and D12 with 50-nm PyC). For reference, the measured EC(T)-values for a high-purity monolithic CVD-SiC (values used to estimate the effects of the SiC seal coat) also are included in Fig. 5. Figure 5 in this report is the same as Fig. 5 in Ref. [5], except the new data for disc sample D12 has been added.

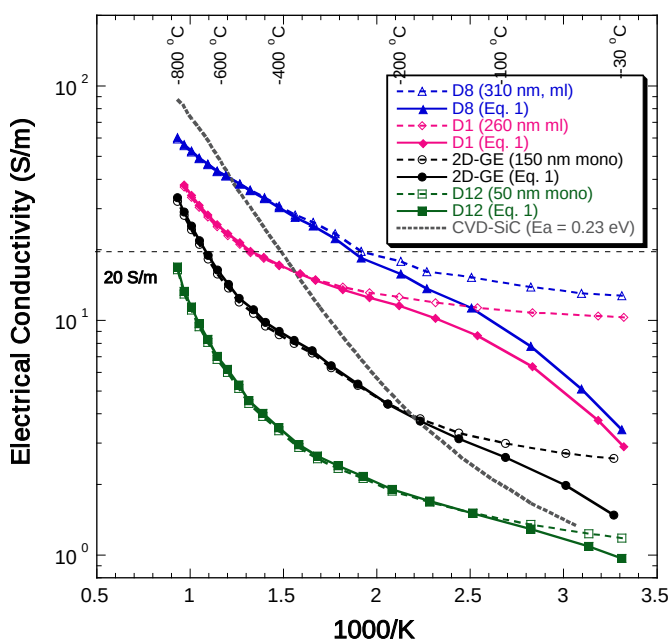


Figure 5. Transverse EC(T) predicted by using Eq. [1] (solid lines) and measured $EC_{int}(T)$ with minimum contact resistance (dashed lines) for four types of 2D-SiC/CVI-SiC. Samples D8 (8HS weave) and D1

(5HS weave) had multilayer PyC/SiC fiber coatings (~310-nm and 260-nm total PyC thickness, respectively), and 2D-GE and D12 (5HS and 8HS weave, respectively) had single layer PyC fiber coatings (~150-nm and 50-nm PyC thickness, respectively). EC(T)-values measured for a high-purity monolithic CVD-SiC with effective activation energy of 0.23 eV also are shown (grey dashed line).

As before [5], for T>~300°C the predicted EC(T)-values are approximately the same as the measured EC_{int}(T)-values for each corresponding sample. For T<~300°C, predicted EC(T)-values begin to deviate more and more below the corresponding sample EC_{int}(T)-values as the temperature decreases. Also, at high temperatures the temperature dependence (slopes of the EC(T)-curves) approaches but remains somewhat less than that of CVD-SiC, at moderate temperatures the slopes are less and deviate more from those of CVD-SiC, and at low temperatures the temperature dependence again approaches that of CVD-SiC. These observations are interpreted: at high temperatures electrical conduction through the SiC matrix and fiber components dominates, at moderate temperatures conduction through the interconnected PyC fiber coating network dominates, and at sufficiently low temperatures conduction becomes limited by the SiC seal coat.

Also, suggested as a possibility in Ref. [5], the predicted transverse EC-values for a 2D-SiC/CVI-SiC composite with a relatively thin (50 nm) PyC fiber coating were below the FCI-application design limit of 20 S/m for all temperatures up to 800ºC.

It is instructive to examine the dependence of the rate of increase of the transverse EC on the total PyC fiber coating thickness. In Figure 6, the ratio of the transverse EC-value for each disc (solid lines) and bar (dashed lines) sample with the corresponding EC-values of the disc or bar sample with a 50-nm thick PyC coating is plotted against the ratio of the total PyC coating thickness for each sample type to 50 nm for two temperatures, a high 700ºC (shown in red) and a low 200ºC (shown in blue).

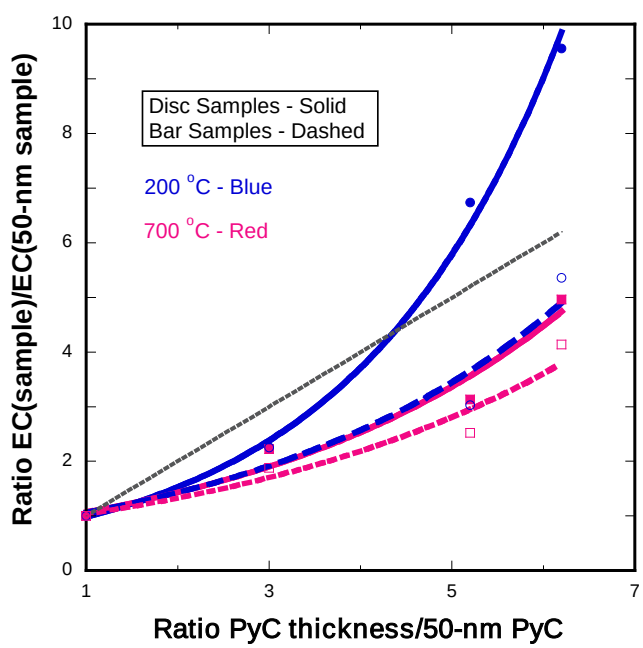


Figure 6. Dependence of transverse (solid lines) and in-plane (dashed lines) EC of 2D-SiC/CVI-SiC on total PyC fiber coating thickness at two temperatures (200ºC in blue and 700ºC in red). The dashed gray line indicates direct proportionality. For guidance, an exponential curve was fit to the data points.

In Figure 6, at either the representative low (200ºC) or high (700ºC) temperatures, the bar sample EC-ratio curves lie below the direct proportionality line. This is because the almost continuous CVI-SiC matrix, which amounts to ~90% of the composite volume, also contributes to the over all in-plane EC. Also, the 700ºC curve lies above the 200ºC curve, which indicates that the SiC matrix EC contribution becomes more important at higher temperatures, as expected for semi-conducting SiC. For the disc sample EC-ratios, the low temperature curve lies below the direct proportionality line, while the high temperature curve starts out below the proportionality line but increasingly tends to exceed the proportionality line as the total PyC thickness increases above 150 nm or so. Apparently, the interconnectivity of the PyC coating network plays an increasingly more important role as the coating thickness increases. Of course, the multilayer PyC/SiC coatings may also result in additional interconnectivity of the carbon network.

CONCLUSIONS

1. The contact resistance is large when using a 2-probe method to measure transverse EC(T) through a 2D-SiC/CVI-SiC plate with a SiC seal coat. The simplest way to estimate these EC(T)-values is to use the 2-probe method to measure $EC_{int}(T)$ of disc samples with seal coat ground off and then calculate EC(T) using Eq. [1]. The effect of contact resistance will be minimized when measuring $EC_{int}(T)$ because now the metallic electrodes make good electrical contact with the highly conductive PyC fiber-coating network with numerous intersections at the ground surfaces. However, to actually minimize the contact resistance for 2D-SiC/CVI-SiC composite with its SiC seal coat ground off extreme care is necessary when preparing the cut interior surfaces to minimize polishing surface damage.

2. The newly predicted transverse EC(T)-values for a 2D-SiC/CVI-SiC composite with a relatively thin 50 nm monolayer PyC fiber coating were below the desired FCI-application limit of 20 S/m for all temperatures up to 800ºC.

3. The in-plane EC(T)-values for the 2D-SiC/CVI-SiC composites with similar fabric weaves but with different PyC fiber coating thicknesses ranged from ~100 to 1000 S/m for total PyC thickness ranging from 50 to 310 nm, respectively. Furthermore, the temperature dependences were much shallower than observed for pure SiC over the RT to 800ºC temperature range (~0.1-100 S/m, respectively). This occurs because the in-plane EC is dominated by conduction along the continuous PyC fiber-coating network lying mostly parallel to the in-plane conduction direction. Also, in-plane EC-values were 10-100 times larger than transverse EC-values, as expected for these 2D materials.

4. The EC in the transverse direction for 2D-SiC/CVI-SiC with PyC fiber coatings is strongly controlled by conduction through the interconnections of the carbon network within and between fiber bundles, especially at moderate temperatures (~300ºC to 700ºC). For higher temperatures, the EC of the SiC matrix plays an increasingly more important role; while at lower temperatures the low EC-values for the SiC seal coat become important.

5. The in-plane EC(T)-values for 2D-SiC/CVI-SiC depend primarily on the high conductivity PyC network pathways, however the almost continuous parallel conduction pathways through the CVI-SiC matrix also contribute. The magnitude of the transverse EC(T)-values depends more on the interconnectivity of the PyC network between fabric layers and within the fiber bundles. The degree of interconnectivity increases for composite with thicker PyC fiber coatings or with multilayer SiC/PyC coatings.

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