Buckling of Magnetically Formed Filler Fiber Columns Under Compression Increases Thermal Resistance of Soft Polymer Composites

Thermally conductive soft composites are in high demand, and aligning the fill material is a potential method of enhancing their thermal performance. In particular, magnetic alignment of nickel particles has previously been demonstrated as an easy and effective way to improve directional thermal conductivity of such composites. However, the effect of compression on the thermal performance of these materials has not yet been investigated. This work investigates the thermal performance of magnetically aligned nickel fibers in a soft polymer matrix under compression. The fibers orient themselves in the direction of the applied magnetic field and align into columns, resulting in a 3× increase in directional thermal conductivity over unaligned composites at a volume fraction of 0.15. Nevertheless, these aligned fiber columns buckle under strain resulting in an increase in the composite thermal resistance. These results highlight potential pitfalls of magnetic filler alignment when designing soft composites for applications where strain is expected such as thermal management of electronics. [DOI: 10.1115/1.4041539]

Introduction

By filling in air gaps, thermal interface materials (TIMs) reduce thermal contact resistance between mating electronic components in integrated circuits. These materials are integral to the operation of cell phones, laptops, servers, and wherever computer chips produce heat. Furthermore, improving the thermal performance of TIMs enables faster speeds and longer lifespans in these systems. Conversely, poor thermal management can lead to accelerated aging and rapid degradation [1-4].

Composites consisting of a soft polymer matrix with high thermal conductivity filler particles are commonly used as TIM “pads.” These soft polymer composites have two primary advantages: (1) the low Young’s modulus allows the TIM to conform to the geometrical imperfections of the two mating surfaces and (2) the polymer pads do not suffer from pump out issues like most thermal greases [2]. However, the soft polymer matrices have a low thermal conductivity of 0.1-0.4 W m⁻¹ K⁻¹ [5,6] that can only be moderately enhanced to around 1.5-3 W m⁻¹ K⁻¹ by solely dispersing traditional high thermal conductivity filler particles [7]. Consequently, much effort has been dedicated to developing novel fillers and their dispersion methods that increase the thermal conductivity of soft polymer composites to the ranges needed for current high performance applications [3,4,8,9].

Thermal conductivity of polymer composites is a function of fill thermal conductivity, fill volume ratio, fill aspect ratio, matrix thermal conductivity, interaction between fill and matrix, fill alignment, and dispersion [7]. In general, an increase in the value of the first four listed parameters will result in an increase in the composite thermal conductivity, as will a better chemical interaction between fill and matrix [10-17]. However, particle dispersion does not necessarily follow this trend—a composite with well-dispersed filler does not necessarily have a higher thermal conductivity than a composite with poorly dispersed filler. This ambiguity exists because aggregation and alignment of filler particles can increase the directional thermal conductivity of the composite [12,18-20]. Since TIM pads only require high heat transfer rates in the normal direction, vertically aligning the fill material in the matrix presents a path for increasing performance while holding all other parameters constant [21-24].

Previous works have demonstrated that aligned fill material in a polymer matrix can greatly enhance the directional thermal conductivity of the composite and that composites with high aspect ratio fill particles benefit most from alignment [25-27]. Flow of the uncured polymer, for example, is an effective method for aligning high aspect ratio particles [28,29]. However, in most microelectronics applications—such as the case of underfill—flow of the uncured composite is perpendicular to the direction of desired fill alignment. An alternative approach that enables high control over the preferential particle direction is alignment by a magnetic field.

Ferrous fill material in a polymer matrix can be easily aligned in a controlled magnetic field [25,30-32]. Furthermore, simple, uniaxial magnetic field alignment of spheroid nickel particles doubles the thermal conductivity of the composite (as compared to the unaligned particle composites), achieving a thermal conductivity enhancement of more than 4× at a fill volume fraction, φ, of 0.3 over the matrix alone [33]. Magnetic alignment of nickel platelets shows an even greater increase due to alignment and can do so at smaller fill volume fractions. For example, Solis et al. showed an enhancement in thermal conductivity of 20× at φ = 0.15 over the matrix material (a 4× increase over unaligned sample) [34]. The authors of these two works [33,34] went on to further explore how various types of magnetic fields affect particle alignment and conclude that the applied magnetic field will align the particles in a structure that is optimal for good thermal transport [35]. Thus, magnetic alignment of fill in a polymer matrix is a simple and effective method for improving the composites thermal performance. However, the thermal performance of soft composites with magnetically aligned particles under compression in ranges relevant to microelectronic applications (strain of at least 25% or more [36]) has not been investigated. In this work, we experimentally fill this knowledge gap by (i) investigating thermal
transport changes caused by magnetically aligned nickel fibers in a soft silicone matrix and (ii) investigating the effects of compression on these composite pads. Intriguingly, we demonstrate that the thermal resistance of the pads with aligned fibers increases under compression. Using further experiments and theoretical arguments, we reveal that this increase stems from buckling of the fiber columns under compressive strain.

**Methods**

**Fabrication.** The matrix material in this work is Smooth-On EcoFlex 00-20, which is a very soft, platinum cured silicone elastomer with a thermal conductivity, \( k \), of \( 0.3\pm0.03 \) \( \text{W m}^{-1} \text{K}^{-1} \) (95% uncertainty). The nickel fibers (50 \( \mu \text{m} \) wide \( \times 20 \) \( \mu \text{m} \) thick \( \times 250 \mu \text{m} \) long from IntraMicron (Aubum, AL), Fig. 1(a)) are mixed into the matrix with a mortar and pestle. Large nickel fibers were selected for this work so that fiber alignment in the polymer matrix could be easily observed and characterized with an optical microscope. The uncured composite is vacuum degassed to remove air bubbles and then poured into a 1.5 mm \( \times 12.7 \text{mm} \times 12.7 \text{mm} \) acrylic mold. The top is placed on the mold, removing any excess material, and magnets (BY0Y02 from K&J Magnetics, Inc., 2 in \( \times 2 \) in \( \times 1/8 \) in, NdFeB, Grade N42) are placed on top and bottom of the mold for aligned fiber composites, as illustrated in Fig. 1(b). The magnetic field strength at the center of the sample is estimated at around 1400 gauss, based on estimates from the manufacturer’s online calculator for magnetic field strength [37]. For unaligned composites, a weight is placed on top of the mold during cure. Since the samples with \( \phi = 0.25 \) and 0.35 are too viscous to pour, they are scooped into the mold and packed in with the pestle. The composites are cured in the mold at room temperature for 3 h.

**Thermal Measurements.** Thermal resistance is measured in the direction of fiber alignment with a stepped bar apparatus (SBA) [38,39], which is based on the ASTM D5470 standard for measuring thin, insulating materials. A linear encoder on the SBA measures the distance between the reference bars and, subsequently, the compressed thickness of the composite sample. Concurrent measurements of applied pressure were also performed using a load cell integrated with the SBA (see Fig. S1, which is available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection). Thermal conductivities are calculated using the measured thermal resistance and thickness of the compressed sample as

\[
k = \frac{t_c}{R}
\]

where \( t_c \) is the compressed thickness of the sample in meters and \( R \) is the measured thermal resistance in \( \text{m}^2 \text{KW}^{-1} \). The average temperature of the samples during thermal measurement is around 55 °C. The system has been validated using reference silicone samples (refer to Ralphs et al. [18] for details).

A thin layer of liquid galinstan (Rotometals) is applied on top and bottom of each sample to minimize contact resistance between the sample and reference bars. Note that the copper bars are not affected by gallium within the timeframe of the experiments [18]. Thus, while the measured values in this paper are effective thermal conductivities and include the thermal contact resistance between the sample and the reference bars, the difference between the measured value and the bulk composite thermal conductivity is assumed to be small. The effect of thermal contact resistance is also further minimized by our use of relatively thick samples that are 1.5 mm thick (no compression) and 0.85 mm thick (full compression with strain = 0.45).

**Buckling.** The buckling behavior of the nickel fiber columns encapsulated in the polymer was observed with an optical microscope (Zeiss Axio Zoom.V16 with an objective lens of 2.3 \( \times \)0.57 FWD and 10.6 mm focal length Zeiss PlanNeoFluar Z) while the composites were compressed in a vise. The effects of the aligned nickel columns buckling are most easily visualized at \( \phi = 0.05 \) (Fig. 5(b) inset and Fig. S2 in supporting information, available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection). This image clearly shows that the aligned columns of nickel fibers buckle with increased compressive strain. As illustrated in Fig. 2, the aligned columns buckle...
outward, radially, which is most likely driven by Poisson’s effect. Specifically, the nickel fiber columns appear to be tracking the continuum mechanics deformation field rather than buckling in random fashion. Since the pressure applied to these composites is not large enough to significantly deform the nickel fibers themselves (under 1 MPa), the length (or arc length) of the aligned nickel columns should remain constant as they buckle. However, because the optical images do not capture out of plane deformations (the columns could be buckling in or out of the plane of focus), it is difficult to confirm this. The increase in thermal resistance with strain is reversible (see Fig. S5 in supporting information for details, available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection), signifying no permanent damage or deformations are incurred. Therefore, tears in the minimal amount of polymer matrix that hold the nickel fiber columns together can be ruled out along with nickel fibers slipping past each other as the composite is compressed. Thus, it is assumed that the length of the buckling nickel fiber columns remain constant as strain increases.

**Image Processing for Fiber Alignment.** Alignment of the nickel fibers was evaluated by image processing with ImageJ, by manually drawing lines on top of the individual fibers. The angle of the fibers ranged from 0 deg to the right to 180 deg on the left with 90 deg corresponding to a fiber aligned from bottom to top of the composite. The angle measurements in Fig. 3 and histograms in Fig. S3 (see “Supplemental Materials” tab for this paper on the ASME Digital Collection) show the results from at least 200 fiber orientation measurements per fiber for both aligned and unaligned composites. The angle measurements were sorted and every fourth sixth angle was plotted in order to distinguish individual data points, depending on how many fiber orientation measurements were available.

**Scanning Electron Microscopy of Nickel Fibers.** Nickel fibers were suspended in ethanol and then drop cast on a piece of a silicon wafer to prepare them for scanning electron microscopy (SEM). Once the ethanol had evaporated, the SEM (Amray 1910 with field emission gun) was conducted at 20 kV, a working distance of 12.1 mm, and a SEM-software defined spot size of 0.0.

**Results and Discussion**

The nickel fibers used in this work have an aspect ratio around 7 (averaging the two transverse fiber dimensions), which is between that of the magnetically aligned spheroid nickel particles (aspect ratio = 1) and nickel platelets (aspect ratio = 20) utilized in previous work on thermal conductivity enhancement through magnetic alignment of filler particles in an epoxy matrix with $k = 0.23 \text{ W m}^{-1} \text{ K}^{-1}$ [33,34]. Consequently, addition of the nickel fibers to the silicone matrix results in a thermal conductivity enhancement greater than that obtained by addition of the spheroid nickel particles but lower than that achieved by addition of the nickel platelets (see Fig. 4(a)). As the nickel fibers are exposed to the magnetic field, the fibers themselves become magnetized and aggregate together forming fiber columns inside the matrix. This segregation and alignment into columns is visually most notable at $\phi = 0.05$, but is also easy to observe with $\phi = 0.15$ (see Fig. 3). At $\phi = 0.25$ and 0.35, there is very little evidence of alignment or reorientation of the fibers. In more quantitative terms, the plots in Figs. 3(b), 3(d), 3(f), and 3(h) show graphical representations of the fiber alignment distribution estimated using image processing from the two-dimensional images. In our definition, the fiber alignment angle varies from 0 deg to 180 deg, where 90 deg corresponds to a line connecting from bottom to top of the composite. From these plots, it is evident that alignment by the magnetic field is less effective at higher $\phi$ (for more info, see Fig. S4 in the “Supplemental Materials” tab for this paper on the ASME Digital Collection). Specifically, the angular distributions of the aligned fibers at $\phi = 0.05$ and $\phi = 0.15$ are highly anisotropic and concentrated around 90 deg (vertical across the composite). In turn, those of the aligned fibers at $\phi = 0.25$ and $\phi = 0.35$ are isotropic (uniformly distributed) and indistinguishable from the isotropic angle distributions of the fibers that were not exposed to magnetic field. While, as expected from our alignment angle definition, for all distributions, the average fiber alignment angle is around 90 deg, the associated standard deviations increase dramatically from 11.3 deg and 27.8 deg for $\phi = 0.05$ and 0.15 to 46.3 deg and 47.6 deg for $\phi = 0.25$ and 0.35. The standard deviation of unaligned samples was measured to be between 48 and 55 deg, and so these angle measurements confirm our qualitative observations of diminishing effectiveness of magnetic field alignment at higher $\phi$.

The decrease of the effect of magnetic field on fiber orientation at higher fill fraction likely stems from increased particle jamming and translates into diminishing thermal conductivity enhancements. Specifically, since the volume of the composites was confined in the mold during exposure to the magnetic field, the ability of the fibers to move in response to the field is highly dependent on their packing. According to Toll [40], the maximum packing factor for these fibers is around 35%, thus explaining the diminishing magnetic alignment as fiber volumetric fraction approaches this limit. In essence, at lower volumetric ratios, particles can freely reorient themselves in response to the magnetic field without interacting with other particles. Near the packing limit, however, volume around the fibers is predominantly occupied by other fibers, which restrict each other’s movements. This diminishing ability of the fibers to align at high volume fractions naturally translates into a decreasing magnetic enhancement in thermal conductivity for composites measured at low strain, $\epsilon$, below 0.05 (see Fig. 4b). Specifically, magnetic alignment more than doubles (from 0.4 to 1.1 W m$^{-1}$ K$^{-1}$) and triples (from 0.7 to 2.2 W m$^{-1}$ K$^{-1}$) the thermal conductivity of the composite at $\phi = 0.05$ and $\phi = 0.15$, respectively. In contrast, at $\phi = 0.25$ magnetic alignment enhances the thermal conductivity only by a factor of 1.3 (from 1.4 to 1.9 W m$^{-1}$ K$^{-1}$) and has no detectable effect at $\phi = 0.35$. Thus, magnetic alignment of fibers provides a significant thermal conductivity enhancement only at fill fractions appreciably below the packing limit.

The plots in Fig. 5 demonstrate that, intriguingly, the thermal properties of the magnetically enhanced composite pads deteriorate with increased compressive strain. Specifically, for the sample with $\phi = 0.05$, inducing compressive strain up to 0.45 decreases the thermal conductivity of the composite from 1.15 to 0.6 W m$^{-1}$ K$^{-1}$ (increases thermal resistance from 1.32 to 3.83 m$^{-2}$ K W$^{-1}$). The corresponding side-view images of the pads under compression shown in the inset in Fig. 5(b) reveal gradual buckling of the fiber columns. Consequently, the counterintuitive degradation of thermal properties of the magnetically enhanced composites under compression likely stems from column-buckling induced changes to the conduction path and/or interparticle thermal resistance.

In order to quantify the role of the nickel fiber column buckling, we have developed two simple models for the thermal conductivity of the compressed composites. The first, most basic model treats the composite as a parallel network of nickel fiber columns and silicone. During compression, the length of the nickel fiber column is assumed to remain constant while the thickness of the matrix material decreases. This simple parallel model is given by

$$k = \frac{t_c}{A} \left( \frac{k_{\text{NFC}} A_{\text{NFC}}}{t_0} + \frac{k_p A_p}{t_c} \right) = \left( \frac{k_{\text{NFC}}}{t_0} + \frac{k_p A_p}{t_c} \right)$$

where $t_c$ is the compressed thickness of the composite, $t_0$ is the uncompressed thickness of the composite, $A$ is the area of the composite, $A_{\text{NFC}}$ is the area of the aligned nickel fiber column (NFC), and $k_p$ is the thermal conductivity of the polymer, and
Fig. 3 Optical microscope images of the aligned (top to bottom) nickel fiber–polymer composites under zero compressive strain at nickel fiber volume fractions of 0.05 (a), 0.15 (c), 0.25 (e), and 0.35 (g) along with fiber alignment measurements ((b), (d), (f), and (h)), respectively. White lines in (a) highlight aligned fiber column axis.
R_{NFC} is calculated from

\[ R_{NFC} = R_p + R_N + R_b \]  

where \( R_p, R_N, \) and \( R_b \) are the total thermal resistances of the polymer, nickel, and interfacial boundary resistance at the nickel–polymer interfaces within the fiber columns, respectively. This model, and all following models, assumes one-dimensional heat transfer, constant temperature boundary conditions on top and bottom of the sample, constant properties, and neglects any geometrical variation from Poisson’s effect as the composite is compressed. For this nickel fiber–polymer column series model, illustrated in Fig. 5(c), we used image processing to roughly estimate that 99% of the column length is occupied by nickel (\( k_N = 90 \text{ W m}^{-1} \text{ K}^{-1} \) \cite{41, 42}), while the remaining 1% is occupied by the polymer (\( k_p = 0.3 \pm 0.03 \text{ W m}^{-1} \text{ K}^{-1}, 95\% \text{ confidence interval} \)). We derived these geometrical estimates by drawing lines on top of aligned nickel fiber columns in the cross-sectional images and used ImageJ to measure the length of distinct polymer junctions between nickel fibers along that line, resulting in an estimate of 1.2 \pm 0.6\% (68\% confidence interval) of the line being occupied by the polymer. This value has a measurable effect on the calculated thermal conductivity of the composite, with a change in the thickness of the polymer in the calculations from 1% of the total column length to 0.5% and 1.5% resulting in a change in thermal conductivities of the uncompressed composite from 1.2 W m\(^{-1}\) K\(^{-1}\) to 1.6 and 1.0 W m\(^{-1}\) K\(^{-1}\), respectively. Since in our simple models we are using a highly idealized nickel–polymer–nickel gap geometry that does not account for
any three-dimensional geometrical imperfections (e.g., fiber misalignment, partial overlapping, etc.), we use the representative rounded-down value of 1% within the models. Use of this value is validated by matching of the calculated and measured thermal conductivity of the uncompressed composite of 1.2 W m\(^{-1}\) K\(^{-1}\).

To calculate this value, we also had to set \(R_b\), which, overall, has a minor effect on thermal conductivity of the composite. Specifically, we set \(R_b\) to \(1.7 \times 10^{-3}\) m\(^2\) KW\(^{-1}\). Such values are typical if little to no effort is taken to achieve a chemically clean interface between particles and matrix [2,43]. We note that in our definition of \(R_b\), it corresponds to the sum over all interfaces in the fiber column. Since there are five to six fibers with 0.25 mm height in the 1.5 mm thick samples, there are about ten such interfaces per column. Thus, the per interface \(R_b\) illustrated in Fig. 5(c) is \(1.7 \times 10^{-6}\) m\(^2\) K\(^{-1}\), corresponding to the middle of the \(10^{-5}\) to \(10^{-7}\) m\(^2\) K\(^{-1}\) range applicable for metal particle-laden composites. With these parameters, the thermal conductivity for the aligned NFCs is estimated at 18 W m\(^{-1}\) K\(^{-1}\). Decreasing \(R_b\) to \(5 \times 10^{-6}\) m\(^2\) K\(^{-1}\) results in a NFC thermal conductivity of 21 W m\(^{-1}\) K\(^{-1}\) and a minor increase of the composite thermal conductivity to 1.3 W m\(^{-1}\) K\(^{-1}\). Thus, while \(R_b\) is incorporated in this model, its effect on the composites’ thermal conductivity is small.

The trend line that lies well above the data in Fig 5(a) and well below the data in Fig 5(b) shows the predicted change in the thermal conductivity and resistivity, respectively, of the composite at \(\delta = 0.05\) as compressive strain increases using the basic parallel resistance model. This model reproduces the experimentally observed decreasing trend in thermal conductivity, but fails to account for the extent of degradation on the thermal conductivity at high strain. It also fails to capture the trend of increasing thermal resistance at high strain. We note that the discrepancy between experimental and predicted trends (decreasing/decreasing in Fig. 5(a) versus increasing/decreasing in Fig. 5(b)) stems from our model definitions. Specifically, both the parallel model of \(k\) in Eq. (2) and the corresponding parallel composite resistance model, \(t_c/kA\), decrease as the sample is compressed. Similarly, compression of the sample should comparably decrease the thermal conductivity of the sample calculated from the measured thermal resistance and sample thickness (see Eq. (1)). However, the measured thermal resistance does not explicitly incorporate the sample thickness and, consequently, can either decrease or increase during compression.

As illustrated in the lower inset in Fig. 5(a), the discrepancy between the experimental data and the basic parallel resistance model could stem from a gradual transition of the mode of heat transfer from purely parallel heat conduction to a mixture of parallel and series conduction. This transition from parallel to series conduction is caused by the nickel columns bending out of parallel with the temperature gradient. From this observed behavior, it is assumed that the transition from parallel to series heat conduction can be scaled with increasing strain and modeled by

\[
k_{\text{parallel+series}} = k_{\text{parallel}}(1 - \epsilon) + k_{\text{series}}\epsilon
\]

where \(k_{\text{parallel}}\) is given previously in Eq. (2) and

\[
k_{\text{series}} = \frac{t_c}{A}\left(\frac{1}{\phi_N t_c + \phi_p k_p} + \frac{1}{k_{\text{NFC}} A} + \frac{1}{k_{\text{p}} A}\right)
\]

where \(\phi_N\) and \(\phi_p\) are the volume fraction of nickel and polymer matrix, respectively. The calculated thermal conductivity and
thermal resistance from this model are shown by the lighter dashed line that more closely fits the data in Figs. 5(a) and 5(b), respectively, for $\phi = 0.05$. This model more accurately represents the unique thermal degradation of these aligned composites under strain and matches fairly well with the experimental values.

Although this hybrid parallel/series model fits our data, there are additional factors that may contribute to the increased thermal resistance under strain. As the aligned nickel fiber columns buckle, the interface between two fibers suffers from localized strain. This localized strain can increase the thermal resistance at the interface by either geometrical changes of the polymer filled gap, $R_{p}$, or by an increase in interfacial boundary resistance between metal and polymer, $R_{b}$. An increase in either of these resistances will increase the resistance at the interfaces, $R_{i}$ (illustrated in Fig. 5(c)) further increasing the resistance of the composite as a whole.

The composites with $\phi = 0.15$ show a similar trend to those with $\phi = 0.05$, decreasing $k$ and increasing $R$ as strain increases, but $\phi = 0.25$ and 0.35 do not follow this trend. Specifically, the plots in Fig. 6 show the measured thermal conductivity and thermal resistance for various $\phi$ with both aligned and unaligned nickel fibers. For composites with $\phi = 0.25$ and above, increasing strain increases $k$ and decreases $R$. These trends stem from the previously discussed composite microstructure evolution during magnetic alignment and buckling of nickel fiber columns under compression. Specifically, compression only increases thermal resistance of samples with filler volume fraction appreciably below the packing limit, for which exposure to the magnetic field resulted in aligned nickel fiber column formation. The fiber columns, in turn, buckle under compression, leading to gradual degradation of thermal properties from mixing of parallel and series heat conduction modes.

Conclusions
Magnetic alignment of nickel fibers with an aspect ratio of 7 in a soft polymer matrix more than triple the directional thermal conductivity of unaligned fibers at $\phi = 0.15$, more than a 7× increase in thermal conductivity over the polymer matrix. Aligned nickel fibers have a higher increase in directional thermal conductivity over the matrix thermal conductivity than aligned spherical nickel particles, but not as high as aligned nickel platelets. At $\phi = 0.05$ and 0.15 with aligned fibers, there is more than a 10% increase in thermal resistance as the composite is compressed. This increase in resistance is caused by a transition from purely parallel heat conduction at $\epsilon \approx 0$ between aligned nickel columns and the polymer matrix to a combination of parallel and series heat conduction scaled with strain.

The increase in thermal resistance as the composite is compressed highlights a potential pitfall when using fill material alignment to increase soft composite thermal conductivity. Many soft composites are put under strain for standard operations and must perform well under those circumstances. Thermal interface materials, for example, are put under a set and constant load when installed, and then undergo further fluctuations in strain as the neighboring components undergo thermal cycling. Thus, the increase in thermal resistance with strain in aligned soft composites must be considered when designing TIMs for these applications.

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Nomenclature
- $A = \text{area}$
- $k = \text{thermal conductivity}$
- $\text{NFC} = \text{n}ickel \text{f}iber \text{c}olumn$
- $R, R_N = \text{thermal} \text{resistance}$
- $R_b = \text{cumulative} \text{thermal} \text{boundary} \text{resistance} \text{at} \text{all} \text{n}ickel-\text{polymer} \text{interfaces} \text{in} \text{an} \text{aligned} \text{NFC}$
- $R_{th} = \text{thermal} \text{boundary} \text{resistance} \text{at} \text{the} \text{interface} \text{between} \text{a} \text{single} \text{fiber} \text{and} \text{the} \text{polymer} \text{matrix} \text{in} \text{the} \text{interface} \text{between} \text{two} \text{fibers} \text{in} \text{a} \text{NFC}$
- $R_i = \text{resistance} \text{at} \text{the} \text{interface} \text{between} \text{two} \text{nickel} \text{fibers} \text{in} \text{a} \text{NFC}$
- $R_{th} = \text{thermal} \text{resistance} \text{of} \text{the} \text{polymer} \text{between} \text{two} \text{nickel} \text{fibers} \text{in} \text{a} \text{NFC}$
- $t = \text{compressed} \text{thickness}$
- $\epsilon = \text{compressive} \text{strain}$
- $\phi = \text{fill} \text{volume} \text{fraction}$

Subscripts
- $N = \text{nickel}$
- $\text{NFC} = \text{n}ickel \text{f}iber \text{c}olumn$
- $P = \text{polymer}$

References

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