Paper ID# B68

Thermal Conductivity of Copoly(ethylene vinyl acetate)/Nano-filler Blends

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Abstract

The development of flexible, thermally conductive fabrics and plastic tubes for the Liquid Cooling and Ventilation Garment (LCVG) are needed to reduce weight and improve the mobility, comfort, and performance of future spacesuits. Such improvements would allow astronauts to operate more efficiently and safely for extended extravehicular activities. As a continuation of our work on the improvement of thermal conductivity (TC) of polymeric materials, nanocomposites were prepared from copoly(ethylene vinyl acetate), trade name Elvax 260™, metallized carbon nanofibers (CNFs), nickel (Ni) nanostrands, boron nitride both alone and as mixtures with aluminum powder. The nanocomposites were prepared by melt mixing at various loading levels and subsequently fabricated into several material forms (i.e., ribbons, tubes, and compression molded plaques) for analysis. Ribbons and tubes were extruded to form samples in which the nanoparticles were aligned in the direction of flow. The degree of dispersion and alignment of the nanoparticles were investigated using high-resolution scanning electron microscopy. Tensile properties of the aligned samples were determined at room temperature. TC measurements were performed using a laser flash (Nanoflash™) technique. The TC of the samples was measured in both the direction of alignment as well as transverse. Tubing of comparable dimensions to that used in the LCVG was extruded from select compositions and the thermal conductivities of the tubes measured.

Keywords: Elvax™, thermal conductivity, extrusion, nanoparticles, nanocomposites

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1. INTRODUCTION

The development of lightweight, high thermal conductivity (TC), flexible materials for potential use in the Liquid Cooling and Ventilation Garment (LCVG) has been of recent interest to NASA. The LCVG is an integral component of the spacesuit that serves to remove body heat from the astronauts. By improving the TC of the LCVG subcomponents (i.e., flexible fabric and cooling tubes), a reduction in the density of the cooling tubes can be realized resulting in reduced weight, improved mobility and comfort. These improvements will enable longer extravehicular excursions by future astronauts. One approach to improving the TC of the polymeric components has been to add nanoparticles which possess high TC.

Combining polymers with an organic or inorganic phase to produce a polymer composite is common in the production and processing of modern plastics. Recently the focus has been to use nanoscale fillers to prepare polymer nanocomposites (PNC) to modify select properties. PNCs are commonly defined as the combination of a polymer matrix resin and inclusions that have at least one dimension in the nanometer size range [1]. PNCs exhibit significant enhancements in certain properties at a far lower concentration than their conventional micro or macro counterparts. Layered clay, expanded graphite (EG), carbon nanofibers (CNFs), and carbon nanotubes (CNTs) are some of the common nanoparticles used in making PNCs. Specialized materials like boron nitride nanotubes, nickel nanostrands, silver nanowires, and metal coated carbon nanofibers are also under investigation.

Nickel (Ni) nanostrands are receiving increasing attention as a conductive additive in polymers and composites. They are very similar to CNFs and multiwalled carbon nanotubes (MWCNTs) but provide the additional electromagnetic, chemical, catalytic, and metallurgical properties of nickel. The strands have diameters ranging from 50 nm up to 2 μm with aspect ratios (length:diameter) in the 50:1 to 500:1 range. The Ni nanostrands are grown as an interconnected three-dimensional lattice of sub-micron and nanostructured strands of Ni and are paramagnetic in nature [2]. Some of these properties are also found in CNFs, although branching, interconnectivity and magnetism are not [3].

Boron nitride (BN) powders are highly pure single crystal hexagonal platelets with particle sizes between 6 and 13 μm that exhibit high TC in the 250-300 W/mK range. The addition of BN to ceramics has been found to result in a considerable degree of anisotropy in TC of the resulting composite. However, the TC of the composite was significantly lower than predicted due to the existence of an interfacial thermal barrier [4]. Boron nitride nanotubes also have the potential to provide improvements in TC when incorporated into polymers [5].

Aluminum containing particles have also been used to enhance the TC of polymers [6]. In our previous studies, good improvements in TC were obtained using MWCNTs, CNFs, and EG as thermally conductive additives [7]. Thus it was of interest to investigate the use of a combination of aluminum (Al) particles and the above mentioned nanofillers as a means of achieving greater improvements in TC.

It has been observed in previous studies that the increase in TC was lower than that predicted by the rule of mixtures. This has been attributed to a thermal transfer barrier at the interface

between the nanofiller and polymer. One potential method of reducing this interfacial resistance is to provide a gradient at the interface by using a coupling agent which has chemical features of both the polymer matrix and nanoparticle. One approach reported the use of covalent bond formation between CNTs and the matrix [8]. This paper also described molecular dynamics simulations on single walled carbon nanotubes (SWCNTs) showed that functionalization with octane on one out of 15 CNT carbon atoms (~7% functionalization) reduced the thermal interface resistance greater than three-fold. However, it was also reported that these attachments can act as phonon scattering centers themselves and reduce the TC of the CNT composite.

Recent research has demonstrated the ability to functionalize nanomaterials such as layered silicate nanoclays, CNTs, CNFs, EG, and silica nanoparticles with a layer of highly conductive metal such as copper, silver, or nickel [9]. Polymer nanocomposites of silver-metallized CNFs have very high electrical conductivity and exhibit excellent shielding effectiveness. Research is underway to develop adhesives for aerospace applications using such metal coated nanofibers [10].

The objective of the work reported herein was to improve the TC of the polymer (i.e., Elvax™ 260) used in the LCVG. The approach was to use thermally conductive nanoparticles and mixtures of these nanoparticles with Al as additives in Elvax™ 260. This polymer matrix was selected for trials with various nanoparticles because it offers a unique combination of processing and performance characteristics. Elvax™ 260 provides outstanding toughness and resilience and maintains flexibility over a broad temperature range without the need for plasticizers. The resin can be used alone or blended to improve the flexibility, resilience, and toughness of other resins.

Melt compounding was chosen as the method to disperse nanoparticles in Elvax™ 260 because the technique involves high shear mixing, which helps to disentangle nanoparticles and disperse them within the matrix. Melt mixing was followed by melt extrusion to fabricate specimens for characterization and testing. The process of extruding nanocomposites through a die and subsequent drawing provides ribbons or tubes that have substantial orientation of nanoparticles in the flow direction. Dispersion of nanoparticles was assessed by high resolution scanning electron microscopy (HRSEM) and samples were characterized for their thermal and mechanical properties by differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), tensile testing, and thermal conductivity measurement. The preparation and characterization of samples containing various loadings of Ni nanostrands, BN powder, metallized CNFs, and Al particles combined with CNTs, CNFs, and EG are discussed.

2. EXPERIMENTAL

2.1 Materials Elvax™ 260, a melt processable ethylene vinyl acetate copolymer obtained from DuPont, was used as-received. Metallized CNFs (Ag, Cu and Ni coated) were obtained from Materials Research Institute, LLC. Ni nanostrands were obtained from Metal Matrix Composites and BN powder (PolarTherm BN, grade PT140) from GE Advanced Ceramics. Al powder was obtained from Alcon-Toyo Industries, Inc. MWCNTs, lot VGE-S16, were procured from the University of Kentucky. CNF, Pyrograph - III - PR-24 HHT was obtained from Applied

Sciences, Inc. and EG (Grade 3775) from Asbury Carbons. The EG already had the galleries expanded by first treating with sulfuric acid and then rapid heating to 900 ºC. The expansion of the graphite was expected to facilitate exfoliation during melt mixing. All other chemicals were obtained from commercial sources and used as-received.

2.2 Physical mixture of 1-dodecylbromide and MWCNTs A three necked 1L round-bottom flask was charged with 20.52 g MWCNTs that had been flame dried under flowing nitrogen and allowed to cool to room temperature. Anhydrous tetrahydrofuran (THF, 575 mL) was added and the mixture sonicated at room temperature in an ULTRASonik 57x bath operating at ~50% power and degas levels for ~4 h. Then 94.31 g of 1-dodecylbromide was added and rinsed in with 50 mL THF. The mixture was stirred at room temperature under nitrogen for ~7 days. It was filtered to recover the product which was subsequently washed in diethyl ether and air dried at ~110 °C for ~ 16 h to afford 20.80 g. The weight % loading of alkylbromide was 1.3 as determined by TGA.

2.3 Processing of Elvax™ 260 with nanofillers Elvax™ 260 was compounded with various nanofillers in a 60 cc internal mixer (Plasticorder PL2000, Brabender) for 3 h at 25 rpm, 125 °C under N_2 purge. 30 wt % Al powder was melt mixed with 20 and 30 wt % loading of MWCNTs, CNFs, and EG. Attempts at mixing the polymer with higher nanofiller loadings (40 wt %) were not possible as there was not enough polymer to bind the nanofillers and Al powder. The loading levels of the nanoparticles in the polymer were 20 wt % for BN and 20 and 30 wt % for Ag, Cu, and Ni coated CNFs, and Ni nanostrands. During mixing the torque was measured and used to calculate sample viscosity. Upon completion of mixing the material was ground in a Mini-Granulator (Kayeness, Inc.) using a 5.5 mm screen. Specimens other than the Al samples were extruded through a Laboratory Mixing Extruder (LME, Dynisco, Inc.) at a barrel temperature of 50 °C and die temperature of 125 °C. Dimensions of the die were 0.38 mm x 19.1 mm. The samples were extruded in the form of continuous ribbons that were 0.1-0.5 mm thick, 10-15 mm wide, and several meters in length. Once extruded, ribbons were cut into pieces approximately 2 cm x 2 cm. The pieces were then stacked on one side of a 9 cm x 2 cm x 3 cm (i.d.) mold and the remainder of the mold filled with Elvax™ 260 pellets. The stacked ribbons were compression molded at 80 °C and 1.72 MPa for 3 h. The molded samples were then sliced using an Isomet 1000 low speed saw with a diamond wafering blade [12.7 cm diameter and 0.5 mm thick with 30 HC diamond (Buehler Ltd)]. Nanocomposite tubes were extruded through a LME at a barrel temperature of 50 °C and a die temperature of 130 °C. The die had an outer diameter of 0.3175 cm and an inner diameter of 0.1588 cm.

For Al containing samples, ribbons were extruded using a 1.27 cm single screw extruder (L:D – 15:1). The screw rpm was 10 and the temperature at the three zones were 50 °C (hopper), 115 °C (barrel mid-section) and 115 °C (die). The CW Brabender extruder was attached to the PL2000. Plaques were prepared from ribbons using compression molding at 80 °C and a pressure of 1.7 MPa for 2 h. Samples for TC analysis were prepared from the plaques by cutting them with a diamond wafering blade as above. Tubing was extruded using a 1.27 cm single screw extruder (L:D – 15:1) with 0.3175 cm outer diameter die head and 0.1588 cm mandrel tip. The screw rpm was 10 and the temperature at the three zones were 50 °C (hopper), 100 °C (barrel mid-section), and 105 °C (die).

2.4 Characterization TGA was performed in air (flow rate – 50 mL/min) on the powder samples using an Auto TGA 2950HR (TA Instruments, DE). The samples were heated at 20 ^oC/min to 100 ^oC, held for 0.5 h to drive off any moisture, and heated to 600 ^oC at a rate of 2.5 ^oC/min. HRSEM images were obtained using a Hitachi S-5200 field emission scanning electron microscope (FE-SEM) equipped with a "through-the-lens" secondary electron detector. Thin-film tensile properties were determined according to a modified version of ASTM D882 using either four or five specimens (0.51 cm wide) per test condition and an Eaton Model 3397-139 11.4 kg load cell on a Sintech 2 test frame. The test specimen gauge length was 5.1 cm and the crosshead speed for film testing was 500 mm/min. Thermal diffusivity of the molded samples as well as ribbons was measured at 25 ^oC using a Netzsch LFA 447 NanoFlash according to ASTM E1461. Sample sizes of 1 cm x 1 cm were cut with the diamond wafering blade as above and sample density calculated by measured sample dimensions and mass. Specific heat of the test sample was measured by comparing the temperature rise of the sample to the temperature rise of a standard reference (Pyrex, TC ~ 1.09 W/mK, Cp ~ 0.76 J/gk) tested under the same conditions. The steady-state TC was calculated through the equation

$$\lambda = C_p D \rho$$

where λ is TC, C_p is specific heat, D is thermal diffusivity, and ρ is the material density. Samples were sprayed with a thin layer of graphite (for uniform thermal adsorption), which was easily rinsed away by solvent (e.g. methanol).

3. RESULTS AND DISCUSSION

3.1 Processing of Elvax™ 260/nanofillers Torque values were obtained during mixing in the Plasticorder and used to calculate melt viscosities. Table 1 shows calculated melt viscosities of various samples at a shear rate of 92.5 sec^{-1} and a temperature of 125 °C. The neat resin had a low viscosity value and in most cases viscosity increased with increasing nanofiller loading. However, the addition of some nanofillers such as Ni nanostrands and BN powder caused a slight reduction in the melt viscosity and it was assumed that these fillers had a plasticizing effect. Figure 1 shows a typical extruded ribbon. The primary purpose of extrusion was to align nanofillers in the flow direction. Stacked ribbons were molded and samples obtained by cutting the molded block in the direction of the dotted line in Figure 2 using a diamond saw. In this way samples could be obtained with alignment both parallel and perpendicular to the direction of TC measurement. Figure 3 shows extruded tubes containing Elvax™ 260/nanofillers. Some alignment of nanofillers in the tubing was expected although it might not be to the same extent as with the extruded ribbons.

3.2. Tensile properties of extruded ribbons Tensile properties were measured at room temperature on Elvax™ 260/nanofiller composites with the results shown in Table 2. The strips used for testing were cut from ribbons prepared from extrusion; hence the nanofillers are somewhat aligned in the stress direction. The results should be considered qualitative due to the variation in thickness across the ribbon surfaces. As expected, in most samples increased filler loading led to increased modulus and decreased elongation. The nanocomposite ribbons containing metallized CNF and Ni nanostrands samples exhibited a reduction in modulus. For

nanocomposites containing Al a significant increase in modulus was observed presumably due to the high filler loading. Loading levels up to 60 wt % nanoadditives caused a significant lowering of elongation of the samples and a reduction in strength.

3.3 HRSEM data Figure 4(a) shows the structure of Ni nanostrands while Figure 4(b) shows Ag-CNF samples. As a result of the metal coating on the nanofibers, their diameters increased and the benefit of large aspect ratio of CNFs was diminished. Figure 5(a) shows the Al particles in the form of flakes. When compounded with MWCNTs and polymer, most of the flakes were coated by the polymer but some are still visible [Figure 5(b)]. Figure 6(a) shows the HRSEM images of the outer surfaces of the Elvax™ 260/Al/MWCNT extruded tubing. The nanotubes are significantly aligned in the direction of extrusion denoted by the arrow. Figure 6(b) shows the cross section of the tubing and MWCNTs are observed projecting out of the polymer matrix.

3.4 Thermal conductivity measurements Since the structure of nanotubes or nanofibers is anisotropic in space, the electrical and thermal properties should be different in the axial (parallel to particle or fiber axis) and transverse (perpendicular to particle or fiber axis) directions. There have been a few reports on the use of dispersed CNTs as thermally conducting fillers in polymer composites and some enhancements in TC were observed [11, 12]. However, the enhanced values are well below those predicted by the rule of mixtures. One reason for this is the existence of interfacial thermal barrier between the matrix and CNT which results in an increase in overall thermal resistance [13]. Huang, et al. [12] proposed a composite structure where all the CNTs embedded in the matrix are aligned from one surface to the opposite side with all the CNT tips revealed on both surfaces. This structure leads to high TC since the CNTs form ideal thermally conducting pathways. Low thermal interface resistances can also be expected as the protruding tips would ensure better thermal contact. It has been reported that alignment of nanofillers in the polymer matrix leads to enhancement of TC [14, 15]. Thus it was decided to process samples with significant nanofiller alignment and measure TC both parallel and perpendicular to the direction of alignment.

Three types of Elvax™ 260/nanofiller samples were measured for TC: extruded ribbon, molded samples cut perpendicular to flow direction, and extruded tubes. Thus measurements were obtained on samples with nanoparticle alignment predominately in the direction of TC measurement (parallel) as well as transverse (perpendicular). Molded samples allow for TC measurement parallel to the nanoparticle alignment while the ribbons allow for TC measurement perpendicular to the nanoparticle alignment. In the case of the tubes, the TC measurement was made parallel to the nanoparticle alignment.

For extruded ribbons, TC was measured perpendicular to the direction of nanofiller alignment (first column in Table 3). Relative to neat Elvax™ 260, the TC increased with increasing loading level of nanofillers. For the BN sample no increase in TC was observed. For metallized CNF samples and Ni nanostrands, the surface of the ribbons was too rough for measurements to be made. In the Al samples 30 wt % MWCNT yielded more than a 3-fold increase in TC and similar increases were observed with CNF and EG samples.

Molded samples cut perpendicular to flow had TC measured in the direction of nanofiller alignment (second column of Table 3). It was observed that TC values of metallized CNFs and Ni nanostrands had a higher value compared to the neat polymer with 50 % improvement for the Ag-CNF samples, 67 % improvement for the Cu-CNF samples, and a 2-fold increase for the Ni-CNF samples. For Ni nanostrands the improvement was about 70 %. For the BN and the Al loaded samples, TC was observed to be significantly greater in the direction of alignment compared to those that were perpendicular to the direction of alignment. The BN sample showed a 2.5-fold improvement in TC. For the Al samples, the improvement in TC was significantly increased. The MWCNT samples at 30 wt % loading exhibited a 10-fold increase in TC relative to neat Elvax™, whereas the CNF samples loaded at 30 wt % showed an 11.3-fold increase. The 20 wt % loading of EG samples showed an improvement by 10.3-fold. The data indicates that the nanofillers, when aligned, form a network that successfully conducts heat by perhaps enabling a more efficient phonon transfer from one filler particle to another. When compared to samples without Al particles, it is seen that the addition of Al significantly improves the TC of the samples, by as much as 30 % as observed in the case of 30 wt % MWCNT.

Extrusion of tubes was carried out with the Al/nanofiller samples as these samples showed promise based on the TC results from the ribbons. HRSEM revealed alignment of the nanofillers along the length of the tubes and TC measurements were also made along the tube axis. As seen in Table 3, 30 wt % loading of MWCNTs improves the TC 18.5-fold (compared to 17-fold in samples without Al) while the same loading of CNF improved TC 18.4-fold (compared to 13-fold in samples without Al). For 30 wt % EG samples, the improvement was 24-fold (compared to 15.5-fold in samples without Al). However, the modified MWCNT (i.e., mixed with dodecylbromide) sample did not show an increase compared to that of the unmodified MWCNTs. In addition to achieving improvement in TC, other characteristics such as flexibility are also important for the envisioned application.

3.5 Flexibility of tubing Disadvantages with the current LCVG are that it is heavy and restricts mobility due to the large number of rigid cooling lines. An analytical study performed by Lockheed Martin Space Operations concluded that significant improvements in weight, comfort, and mobility of the LCVG could be achieved by increasing the TC of the fabric and plastic cooling tubes [16]. Although the incorporation of various nanofillers has improved the TC significantly, it is also necessary to ensure that the flexibility of the cooling tubes are not compromised so that they can be effectively woven into the fabric. Flexibility of the extruded tubes was tested by using a series of stainless steel cylinders of varying diameter. Each tube was wound around the cylinder of a particular diameter and the smallest diameter that the tube could be wound around without kinking was noted. Table 4 shows the data from the flexibility tests. It was observed that for Al loaded samples (Table 4a) at loading levels of 20 wt %, CNF, EG, MWCNT, and modified MWCNT filled Elvax™ 260 had high flexibility. At 30 wt % loading level, only the EG samples showed kinking at the smallest diameter. This is a significant improvement over samples without Al (Table 4b) where only the CNF and modified MWCNT samples showed no kinking while the EG samples showed a higher tendency to kink.

4. SUMMARY

Elvax™ 260 was mixed with various nanofillers to prepare nanocomposites with increased TC. After initial mixing, nanocomposites were extruded into ribbons or tubes. HRSEM revealed significant alignment of nanofillers in the direction of extrusion. TC measurements were made both perpendicular to and in the direction of alignment of nanofillers. For the tubes, TC measurement was made only in the direction of nanoparticle alignment. The largest improvement in TC was achieved when the measurement was performed in the direction of alignment. When all three types of samples were compared, the extruded tubes showed the highest TC. Improvements in TC did not approach those expected based on the rule of mixtures presumably due to poor phonon transfer through the matrix. It was observed that the addition of Al particles to the polymer loaded with nanofillers improves the TC significantly without compromising flexibility. Finally when the TC, flexibility, and cost of material were taken into consideration, it was concluded that samples with 20 and 30 wt % loading levels of EG and 30 wt % Al powder had excellent flexibility, very high TC, and cost substantially less than MWCNTs. The use of Al powder and EG to improve the TC of the cooling tubes of the LCVG subcomponents appears attractive and more sophisticated testing of cooling tubes comprised of these materials is warranted.

5. ACKNOWLEDGEMENT

6. FIGURES AND TABLES

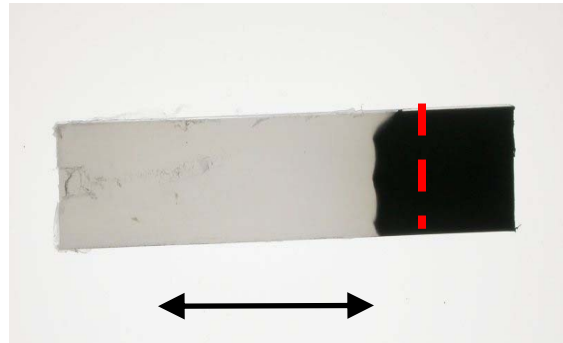Figure 1: Ribbon of Elvax™ 260/nanofillers

Figure 2: Plaque showing cut direction and nanofiller alignment (arrow)

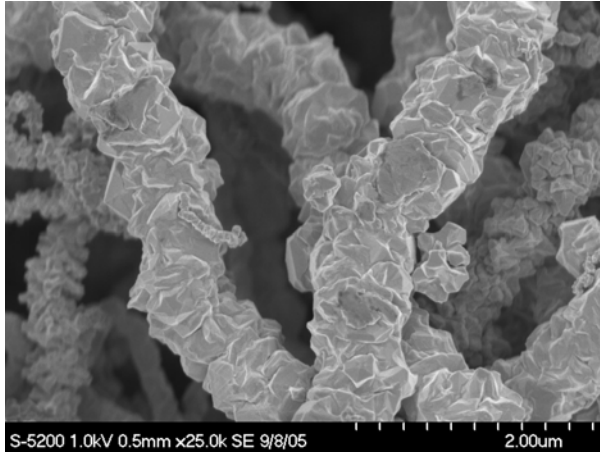Figure 3: Extruded tubes of Elvax™ 260/nanofillers
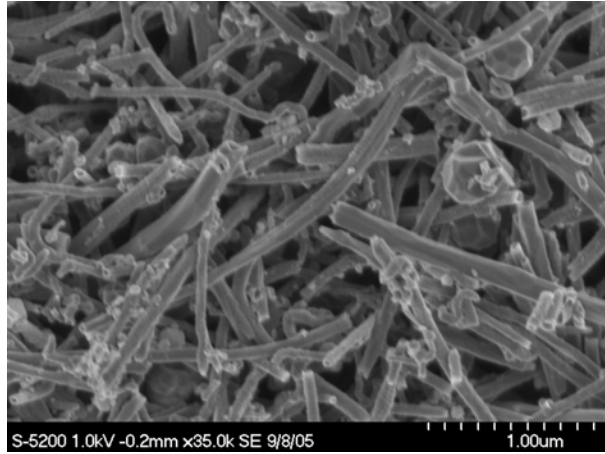
Figure 4(a): Nickel Nanostrands
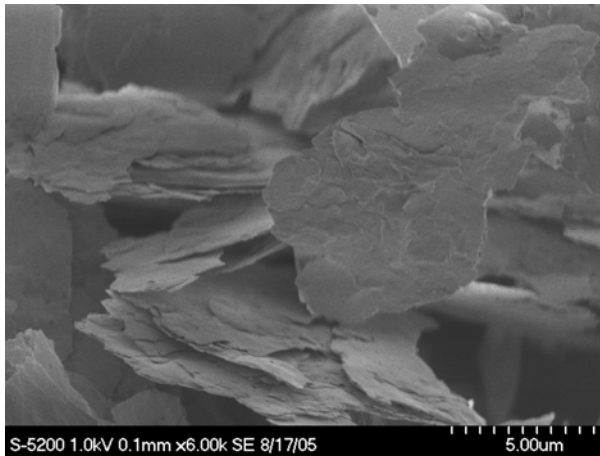

Figure 4(b): Ag-CNF
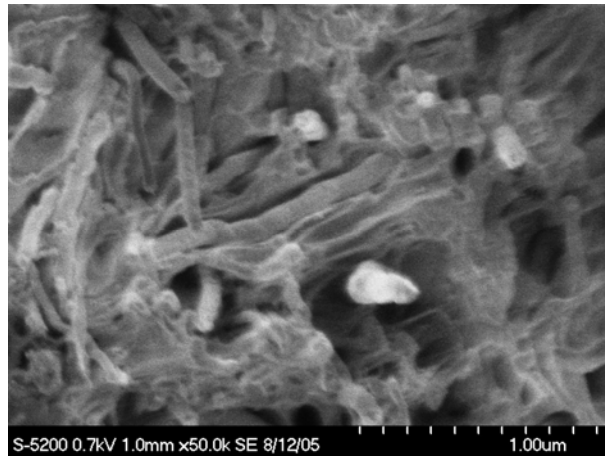

Figure 5(a): Al powder
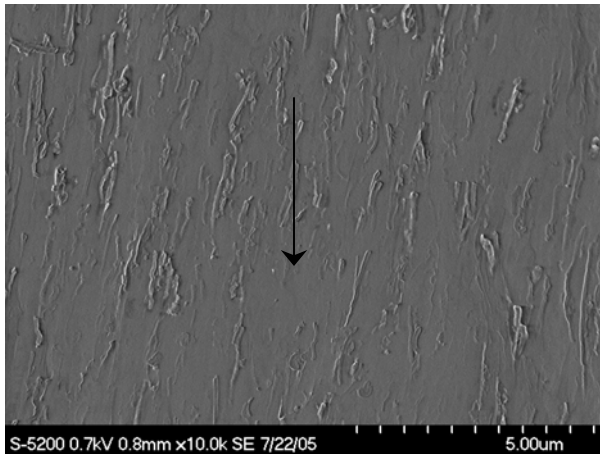

Figure 5(b): 30 wt % Al/ 30 wt % MWCNT

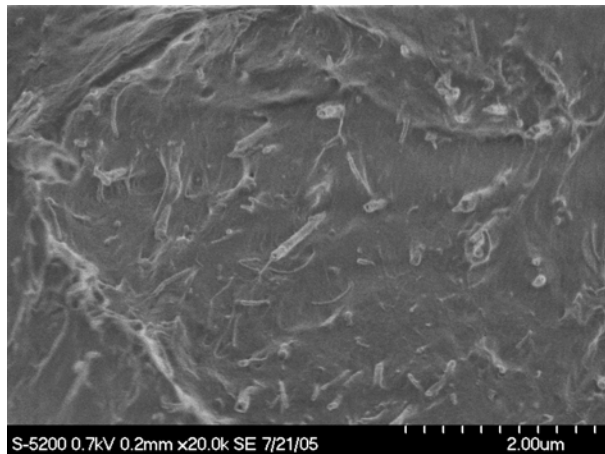Figure 6(a): 30 wt % Al/30 wt % MWCNT

Figure 6(b): 30 wt % Al/20 wt % MWCNT

Table 1: Melt viscosities of Elvax™ 260/nanofiller samples:

Elvax 260™ + Nanofiller(s)	Melt viscosity, Pa-sec
None (neat Elvax 260™)	1001
20 wt % Ag-CNF	940
30 wt % Ag-CNF	1131
20 wt % Cu-CNF	1046
30 wt % Cu-CNF	1067
20 wt % Ni-CNF	1338
30 wt % Ni-CNF	1250
20 wt % Ni-nanostrands	922
30 wt % Ni-nanostrands	849
20 wt % BN	887
30 wt % Al + 20 wt % MWCNT	1927
30 wt % Al + 30 wt % MWCNT	2587
30 wt % Al + 20 wt % mod MWCNT	1907
30 wt % Al + 20 wt % CNF	1951
30 wt % Al + 30 wt % CNF	2564
30 wt % Al + 20 wt % EG	1418
30 wt % Al + 30 wt % EG	1604

Shear rate: 92.5/sec, Temperature: 125 ^{o}C

Table 2: Tensile properties of Elvax™ 260/nanofiller samples at room temperature:

Elvax 260™ + Nanofiller(s)	Modulus, GPa	Strength, MPa	Elongation, %
None (neat Elvax 260™)	0.014 ± 0.001	17.8 ± 0.2	900 ± 15
20 wt % Ag-CNF	0.017 ± 0.001	16.0 ± 0.1	814 ± 57
30 wt % Ag-CNF	0.014 ± 0.0003	14.1 ± 1.6	842 ± 45
20 wt % Cu-CNF	0.009 ± 0.003	13.2 ± 2.4	835 ± 22
30 wt % Cu-CNF	0.007 ± 0.003	11.0 ± 3.4	15.5 ±- 1
20 wt % Ni-CNF	0.007 ± 0.002	10.2 ± 2.6	748 ± 59
30 wt % Ni-CNF	0.013 ± 0.001	9.2 ± 0.8	538 ± 41
20 wt % Ni-nanostrands	0.012 ± 0.003	16.2 ± 1.0	872 ± 32
30 wt % Ni-nanostrands	0.012 ± 0.003	5.8 ± 1.7	531 ± 77
20 wt % BN	0.023 ± 0.003	16.7 ± 3.0	714 ±52
30 wt % Al + 20 wt % MWCNT	0.140 ± 0.01	11.4 ± 1.3	49 ± 7
30 wt % Al + 30 wt % MWCNT	*	*	*
30 wt % Al + 20 wt % mod MWCNT	0.087 ± 0.008	8.9 ± 1.0	90 ± 18
30 wt % Al + 20 wt % CNF	0.065 ± 0.004	6.6 ± 2.2	149 ± 66
0 wt % Al + 30 wt % CNF	*	*	*
30 wt % Al + 20 wt % EG	0.106 ± 0.011	8.3 ± 0.8	95 ± 30
30 wt % Al + 30 wt % EG	0.179 ± 0.035	11.7 ± 0.5	61 ± 10

* Poor quality ribbon

Table 3: TC of Elvax™ 260/nanofiller samples:

Elvax 260™ + Nanofiller(s)	Thermal Conductivity (perpendicular), W/mK	Thermal Conductivity (parallel), W/mK	Thermal Conductivity (tubes), W/mK
None (neat Elvax 260™)	0.311	0.324	0.26
20 wt % Ag-CNF	0.346	0.488	--
0 wt % Ag-CNF	--	0.484	--
20 wt % Cu-CNF	--	0.447	--
30 wt % Cu-CNF	--	0.540	--
20 wt % Ni-CNF	--	0.523	--
30 wt % Ni-CNF	--	0.660	--
20 wt % Ni-nanostrands	--	0.526	--
30 wt % Ni-nanostrands	--	0.550	--
20 wt % BN	0.311	0.866	--
30 wt % Al + 20 wt % MWCNT	0.725	3.299	3.45
30 wt % Al + 30 wt % MWCNT	1.025	3.853	4.82
30 wt % Al + 20 wt % mod MWCNT	0.691	2.551	2.75
30 wt % Al + 20 wt % CNF	0.734	2.533	2.78
30 wt % Al + 30 wt % CNF	0.983	3.645	4.80
30 wt % Al + 20 wt % EG	0.857	3.337	2.73
30 wt % Al + 30 wt % EG	--	--	6.24
20 wt % MWCNT	0.356	2.318	2.93
20 wt % mod MWCNT	0.573	3.395	3.36
30 wt % MWCNT	0.469	2.942	4.40
20 wt % CNF	0.409	1.949	3.02
30 wt % CNF	0.486	2.872	3.51
20 wt % EG	0.399	3.000	3.80
30 wt % EG	0.509	4.359	4.04

Table 4a: Radius of Curvature of Elvax™ 260/30 wt % Al/nanofiller tubing:

Diameter, cm	20 wt % MWCNT	30 wt % MWCNT	20 wt % CNF	30 wt % CNF	20 wt % EG	30 wt % EG	20 wt % mod MWCNT
4.175	√	√	√	√	√	√	√
3.774	√	√	√	√	√	√	√
3.581	√	√	√	√	√	√	√
3.274	√	√	√	√	√	√	√
3.208	√	√	√	√	√	√	√
2.982	√	√	√	√	√	√	√
2.855	√	√	√	√	√	√	√
2.563	√	√	√	√	√	√	√
2.423	√	√	√	√	√	X	√

√ = tube did not kink

X = tube kinked

Table 4b: Radius of Curvature of Elvax™ 260/nanofiller tubing:

Diameter, cm	20 wt % MWCNT	30 wt % MWCNT	20 wt % CNF	30 wt % CNF	20 wt % EG	30 wt % EG	20 wt % mod MWCNT
4.175	√	√	√	√	√	√	√
3.774	√	√	√	√	√	√	√
3.581	√	√	√	√	√	√	√
3.274	√	√	√	√	√	√	√
3.208	√	√	√	√	√	X	√
2.982	√	X	√	√	X	X	√
2.855	√	X	√	√	X	X	√
2.563	X	X	√	√	X	X	√
2.423	X	X	√	√	X	X	√

√ = tube did not kink

X = tube kinked

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