# A review and analysis of electrical percolation in carbon nanotube polymer composites

Wolfgang Bauhofer [1], Josef Z. Kovacs

*Institut für Optische und Elektronische Materialien, Technische Universität Hamburg-Harburg, D-21073 Hamburg, Germany*

## Abstract

We review experimental and theoretical work on electrical percolation of carbon nanotubes (CNT) in polymer composites. We give a comprehensive survey of published data together with an attempt of systematization. Parameters like CNT type, synthesis method, treatment and dimensionality as well as polymer type and dispersion method are evaluated with respect to their impact on percolation threshold, scaling law exponent and maximum conductivity of the composite. Validity as well as limitations of commonly used statistical percolation theories are discussed, in particular with respect to the recently reported existence of a lower kinetic (allowing for re-aggregation) and a higher statistical percolation threshold.

## 1. Introduction

Electrical percolation in mixtures of electrically conducting and non-conducting materials is a widely investigated field which has been covered by several textbooks [1],2]. The observation of a conductivity threshold in polymer/carbon nanotube (CNT) composites [3] has triggered world-wide activities in this area. A recent synopsis has been given by Winey et al. [4].

By now, almost 200 publications report on the electrical percolation threshold of CNT in different polymer systems. The variation of many parameters like CNT type, synthesis method, treatment and dimensionality as well as polymer type and dispersion method, however, impeded a thorough understanding of the processes involved. This article is an attempt to condense a comprehensive collection of published data in order to extract general dependencies of the percolation threshold, the scaling law exponent and the maximal conductivity on the above mentioned parameters.

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[1] Corresponding author. Tel.: +49 40 42878 3047; Fax: +49 40 42878 2229. *E-mail address:* bauhofer@tuhh.de (Prof. Dr. rer. nat. W. Bauhofer).

## 2. Percolation thresholds

Since the early observation of *percolation-dominated* electrical conductivity in a CNT/PmPV composite by Coleman et al. [3] more than 30 polymer matrices have been investigated with respect to percolation of CNT filler loading. Table 1 represents a comprehensive collection of published data in this field. The table is organized as follows: The polymer matrices in column 1 are arranged alphabetically, the data for a given polymer are arranged with increasing percolation threshold. The acronyms used to denote the polymers are defined below the table. Type (single/double/multi wall), synthesis method (arc discharge, chemical vapor deposition, laser vaporization), manufacturer, state (entangled or non-entangled), additional treatment (purification, functionalization) and aspect ratio of the CNT are given in columns 2-5 as far as the information is available from the publications. In columns 6 and 7 dispersion method and solvent in the case of solution processing are specified. Finally, electrical characteristics like percolation threshold $\Phi_C$, critical exponent t and maximum observed conductivity $\sigma_{max}$ are listed in columns 8-10. All percolation thresholds and filler concentrations are given in weight% (wt%). Wherever the original data are given in vol%, we use the conversion relations vol% = wt% for single wall nanotubes (SWCNT) and vol% = 2 wt% for multi wall nanotubes (MWCNT) independent of the polymer matrix. We are convinced that the resulting inaccuracies have no significant effect on the interpretation of the experimental results.
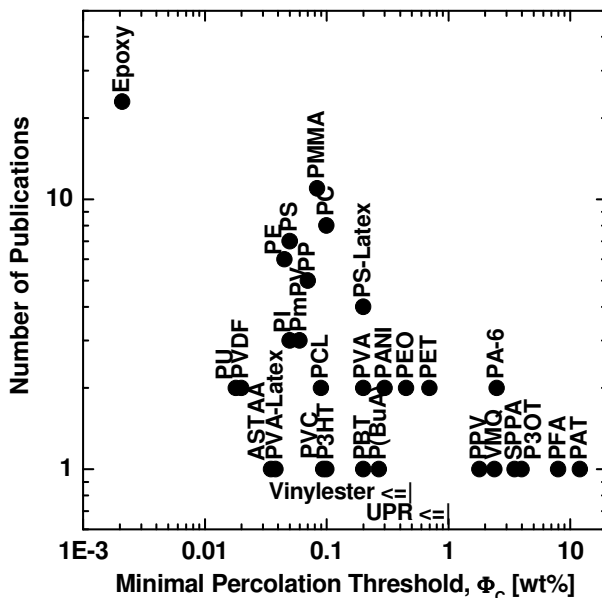


*Fig. 1. Plot of the total number of publications per polymer system versus the minimum percolation threshold achieved with the respective system.*

Inspection of Table 1 clearly shows a large spread in the number of investigations for different polymer matrices. For 14 polymers listed in the table a single publication was available to us while 23 papers referring to an epoxy matrix could be included. This imbalance has to be taken into account when evaluating Table 1 with respect to percolation thresholds $\Phi_C$. This fact is visualized by Fig. 1, which shows the minimum observed $\Phi_C$ together with the number of publications for each polymer matrix. We notice that for all $\Phi_C > 0.2$ wt% no more than two papers could be exploited. This finding supports our belief that with optimized dispersion methods a percolation threshold $\Phi_C \approx 0.1$ wt% might be obtainable for nearly any CNT/polymer system. For a statistical distribution of filler particles the excluded volume concept [5] gives $\Phi_C \approx 1/\eta$ in the limit of large aspect ratios $\eta$. A typical aspect ratio $\eta \approx 1000$ for CNT reproduces the above mentioned value of 0.1 wt%. Thus, we relate

this value to the statistical percolation threshold. Percolation thresholds significantly lower than $\Phi_C \approx 0.1$ wt% are attributed to kinetic percolation which allows for particle movement and re-aggregation. This interpretation particularly applies to results published for CNT/epoxy composites [6],7].

The observation of <u>two</u> percolation thresholds in the same MWCNT/epoxy system was recently reported by Kovacs et al. [8]. Statistical percolation refers to a situation where randomly distributed filler particles form percolating paths. In kinetic percolation, the particles are free to move and thereby can form a conducting network at much lower particle concentrations. Particle movement can be caused by diffusion, convection, shearing, or external fields. Figure 2 shows the cured sample conductivity vs. filler concentration for three different methods of sample preparation: slow (50 rpm), medium (500 rpm), and fast (2000 rpm) stirring of the dispersion for 5 min at elevated temperature (80 °C) prior to curing. Fast stirring leads to statistical percolation near 0.1 wt%. Slow or medium stirring induce aggregation of CNT and, thereby,
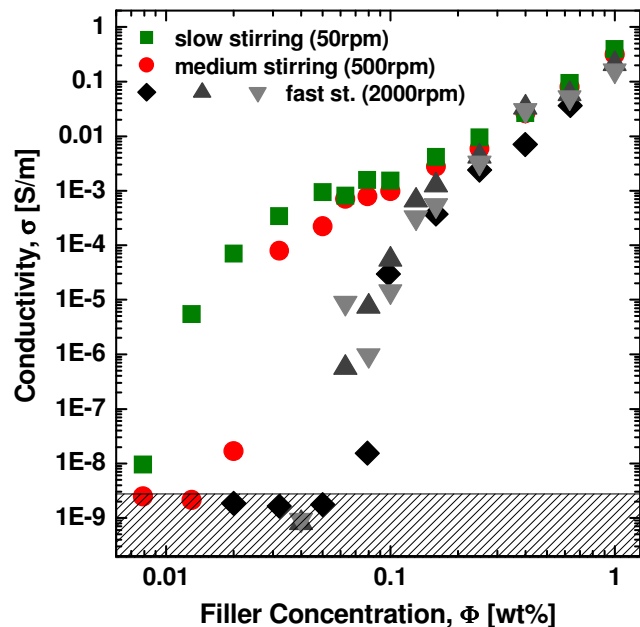


Fig. 2. Comparative log–log plot of the nanocomposite (MWCNT/epoxy) conductivity as a function of the nanotube weight fraction for the three different sample preparation methods: slow (50 rpm), medium (500 rpm), and fast (2000 rpm) stirring of the dispersion for 5 minutes at elevated temperature (80 °C) prior to curing.

lead to kinetic percolation at significantly lower filler concentrations. However, when the filler concentration approaches the statistical percolation threshold, the effect of stirring and thereby the effect of particle movement vanishes. This effect manifests itself by a change in slope around 0.1 wt% in the conductivity curve for slow and medium stirring.

While stirring produces a rather complicated shear state, controlled shear can be applied to a CNT/polymer suspension in a rheometer. Rheo-optical studies of flow-induced clustering of CNT have first been reported by Erik Hobbie's group at NIST [9] using MWCNT/polyisobutylene suspensions. Rheological measurements and associated optical microstructural observations of MWCNT suspended in epoxy have been described by Rahatekar et al. [10]. Incorporation of 0.35 wt% MWCNT enhanced the low shear rate viscosity by a factor of 20. At higher shear rates, the suspension viscosity asymptotically thinned to the viscosity of the matrix alone. The authors conjecture that shear thinning is connected with the breaking of interconnected networks between CNT and/or aggregates of CNT, and not by CNT alignment. However, at low concentrations (0.035 wt%) aligning was observed instead of macroscopic aggregate formation. We

have observed shear induced aggregation also for low concentrations, as depicted in Fig. 3.
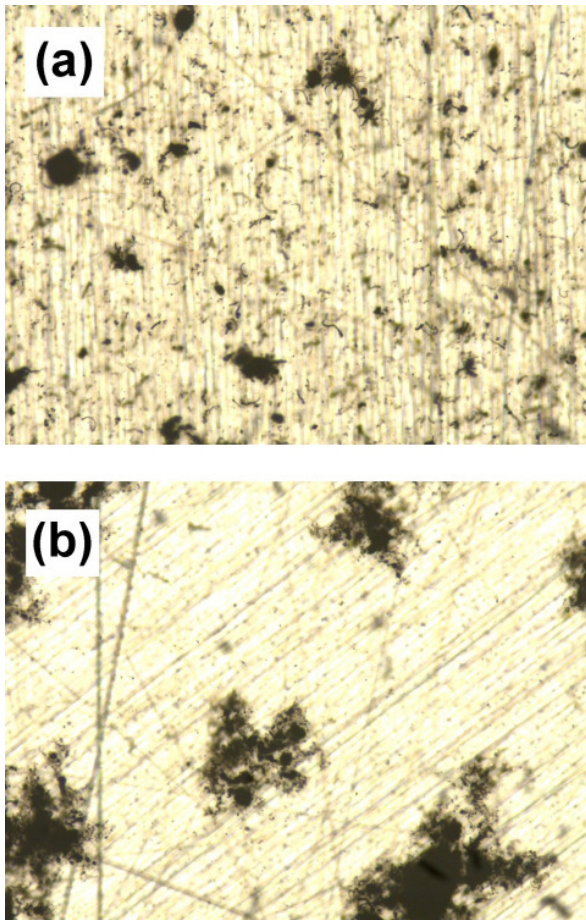


Fig. 3. Optical micrographs of a liquid epoxy composite containing 0.05 wt% MWCNT in the initial, dispersed state (a) and after shearing with 0.1 s$^{-1}$ at 70°C for 60 minutes (b). The width of the image is 1 mm.
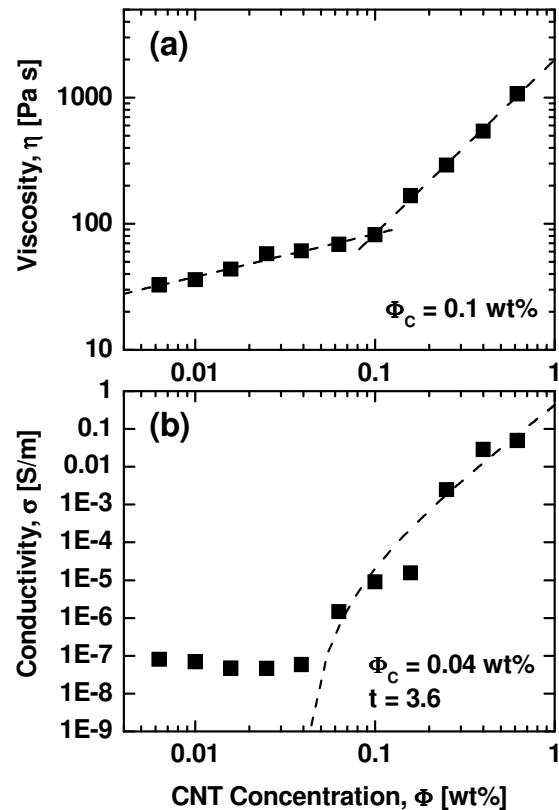


Fig. 4. Simultaneous measurement of the nanocomposite (MWCNT/epoxy) viscosity (a) and electrical conductivity (b) as function of the nanotube weight fraction, performed in the liquid state prior to curing at 0.1 s$^{-1}$ and 20°C. The rheological percolation threshold is located at 0.1 wt% and the electrical one at 0.04 wt%.

Contradicting results have been published concerning the dependence of the percolation threshold on the aspect ratio. According to the excluded volume analysis of Celzard et al. [11] the percolation threshold of a fiber suspension should decrease with increasing aspect ratio. The results of Bai et al. [12] yield a decreasing percolation threshold with increasing CNT length while Martin et al. [13] find an increasing percolation threshold with increasing CNT length. This inconsistency may be solved when looking at the type of the respective percolation thresholds. Bai et al. most likely obtained statistical thresholds while Martin et al. definitely achieved kinetic percolation. Since all theoretical analyses so far ignore the movement of filler particles, they can only predict the dependence of the statistical percolation threshold on the filler aspect ratio.

The effect of CNT alignment on percolation conductivity in SWCNT/PMMA composites has been investigated by Du et al. [14]. The SWCNT were aligned by melt fiber spinning, various levels of alignment could be obtained by controlling the extensional flow in the

spinning process. As a function of alignment the conductivity exhibits a power-law behavior. Highest conductivities occur for slightly aligned, rather than isotropic CNT. A theoretical investigation of the effects of CNT alignment on percolation resistivity using Monte Carlo simulations was recently published by Behnam et al. [15]: *Minimum resistivity occurred for a partially aligned rather than a perfectly aligned nanotube film.*

The dependences of rheological parameters on filler concentration yield a rheological percolation threshold which, in general, occurs at lower concentrations than electrical percolation. Filler particles can interact with each other via polymer chains whereas direct contact between them is required for electrical conduction. For the thermoplastic system SWNT/PMMA, Du et al. [16] indeed observe a rheological threshold at 0.12 wt% well below the electrical threshold at 0.39 wt%. A complementary behavior is found for the thermoset system MWNT/epoxy (see Fig. 4). Due to the lack of polymer chains in the liquid state of thermoset systems, the electrical percolation threshold is encountered first, at around 0.04 wt%. Rheological percolation is reached at 0.1 wt%, where a strong physical interaction between the filler particles is ensured.

## 3. Maximum conductivities

Maximum conductivities of 10,000 S/m have been reported for PMMA containing 10 wt% $SOCl_2$ treated SWCNT [17], of 3000 S/m for PANI filled with 15 wt% SWCNT [18], and of 2000 S/m for PU with 15 wt% MWCNT [19].[2] The percolation thresholds found for the above mentioned systems, i.e., 0.17 wt%, 0.3 wt%, and 1 wt%, respectively, suggest a correlation between percolation threshold and maximum conductivity[3]. Indeed, this finding seems to be true especially for composites based on the same matrix system. It is worth mentioning that the conductivity of composites with identical filler concentration seems to vary – with some exceptions – by only one or two orders of magnitude for identical matrices, but by 10 or more orders of magnitude for different matrices.

We first address the conductivity variation caused by different fillers in the same matrix. Interestingly, type (SWCNT or MWCNT) and treatment (purification, oxidation) of the nanotubes do not show a clear impact on the maximum conductivity (see Table 1). In Fig. 5 the maximum conductivities of all reviewed data are plotted versus their respective filler concentration value. We want to point out that the maximum conductivities of Fig. 5 refer to the maximum values reported in a given publication. In general, these values are significantly lower than conductivities obtained at the maximum attainable concentrations with a respective polymer and processing method.

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[2] Even higher conductivities can be found in publications that do not analyze the electrical percolation threshold or that report on conductive polymer matrices like protonated PANI. These publications are not considered in our review.

[3] The plot (not shown) of the maximum conductivities versus the percolation thresholds has to be subdivided into data sets of comparable CNT concentrations, as the reported maximum concentrations and thus the maxumim conductivities vary considerably even for similar percolation thresholds. Within each data set an indirect proportionality between the maximum conductivities and the percolation thresholds could be identified.
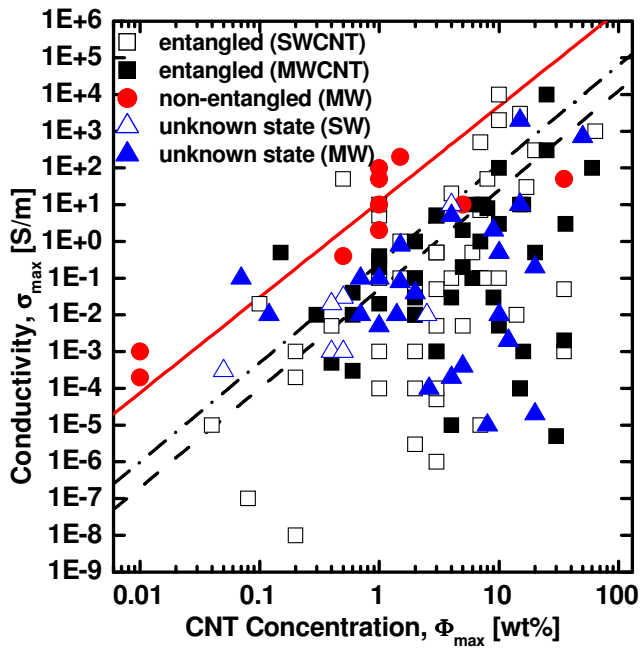
Fig. 5. Comparative log–log plot of maximum conductivity versus respective CNT concentration for all the data in Table 1. The dash-dotted line denotes the dependence $\sigma = 2500 \cdot \Phi^{2.7}$ S/m found for entangled MWCNT in an epoxy matrix [8] while the solid line indicates a similar dependence $\sigma = 120000 \cdot \Phi^{2.6}$ found for non-entangled MWCNT in the same matrix system (unpublished). All data below the dashed line ($\sigma = 500 \cdot \Phi^{2.7}$ S/m for low conductive CNT) are most likely dominated by tunneling between the CNT.

The data points spread over a wide conductivity and concentration range, but principally stay below the dash-dotted line. There are some exceptions, most of them at concentrations above 10 wt%, where a homogeneous suspension probably is not reached. The dash-dotted line denotes the dependence $\sigma = 2500 \cdot \Phi^{2.7}$ S/m found in [8] for entangled MWCNT in an epoxy matrix above the statistical percolation threshold. This line seems to represent the maximum achievable conductivities for entangled MWCNT that are widespread in composite research as their production is fast and cheap. Unpublished results from Kovacs et al. on non-entangled MWCNT (that grow like trees in a forest) show similar power law dependencies above the statistical percolation threshold, the conductivities however are shifted upwards by a factor of 50 (solid line). These findings as well as results of other groups on various matrix systems (see Table 1) suggest that non-entangled MWCNT give much higher composite conductivities than entangled ones. This difference can be explained in two alternative ways. Either the entangled MWCNT could not be dispersed homogeneously and therefore their intrinsic conductivity cannot be extracted from a formula like $\sigma \approx \sigma_0 \cdot \Phi^t$. Or, the intrinsic conductivities of entangled and non-entangled MWCNT truly differ by a factor of 50 (possibly because the straight growing non-entangled MWCNT are less defective). Taking 500 S/m as a lower conductivity limit for highly defective MWCNT we still find many reported data below the dashed line ($\sigma = 500 \cdot \Phi^{2.7}$ S/m). In these cases, we most probably have to consider tunneling through polymer barriers between CNT. Comparing the shift (from one line to another) attributed to different intrinsic nanotube conductivities with the conductivity scattering below the dashed line we conclude that polymer tunneling barriers have a dominant effect on the overall composite conductivity. Definite conclusions on how to avoid this polymer sheathing and maximize conductivity cannot be drawn from the analyzed data. As good dispersions usually imply the formation of a polymer layer around each CNT, we believe that the best dispersions not necessarily lead to the highest conductivities. It seems that solvent processing techniques [88] or shear induced re-aggregation [8] sometimes improve the electrical performance of composites by preventing an overall sheathing or reducing the sheath thickness, respectively.

Comparing different matrices the conductivity variations are much higher than for different fillers. Again, this can only be explained with the extreme distance dependence of tunneling through polymer barriers between CNT. It seems that some polymer types and processing methods favor the formation of insulating polymer coatings of different thicknesses on the CNT. According to Connor et al. [20] tunneling between CNT separated by a thin isolating layer should lead to a dependence of the form

$$\ln \sigma_{DC} \sim - \Phi^{-1/3}$$

between DC conductivity and filler load. A number of investigations seem to confirm this relation. However, as shown in Fig. 6 and discussed in [8], an unambiguous determination of the exponent is not possible.

The mechanism of charge transport in CNT/polymer composites has also been addressed by temperature dependent conductivity measurements. Kim et al. [21] have fitted their experimental results to different theoretical dependencies derived by Mott [22] and by Sheng et al. [23] based on variable range hopping in the former case and fluctuation induced tunneling in the latter. Again, an unambiguous assignment seems difficult.

## 4. Theoretical approaches

The concept of excluded volume has proven to be a powerful method to estimate the percolation threshold of composites containing statistically dispersed non-spherical particles. The concept is based on the idea that the percolation threshold is not linked to the true volume of the filler particles but rather to their excluded volume $V_{ex}$. The excluded volume is defined as the volume around an object in which the center of another similarly shaped object is not allowed to penetrate [24]. $<V_{ex}>$ represents the excluded volume of an object averaged over the orientational distribution characterizing the system objects.

For randomly oriented cylinders with volume $V = W^2 L \pi / 4$ and high aspect ratio $\eta = L/W$,

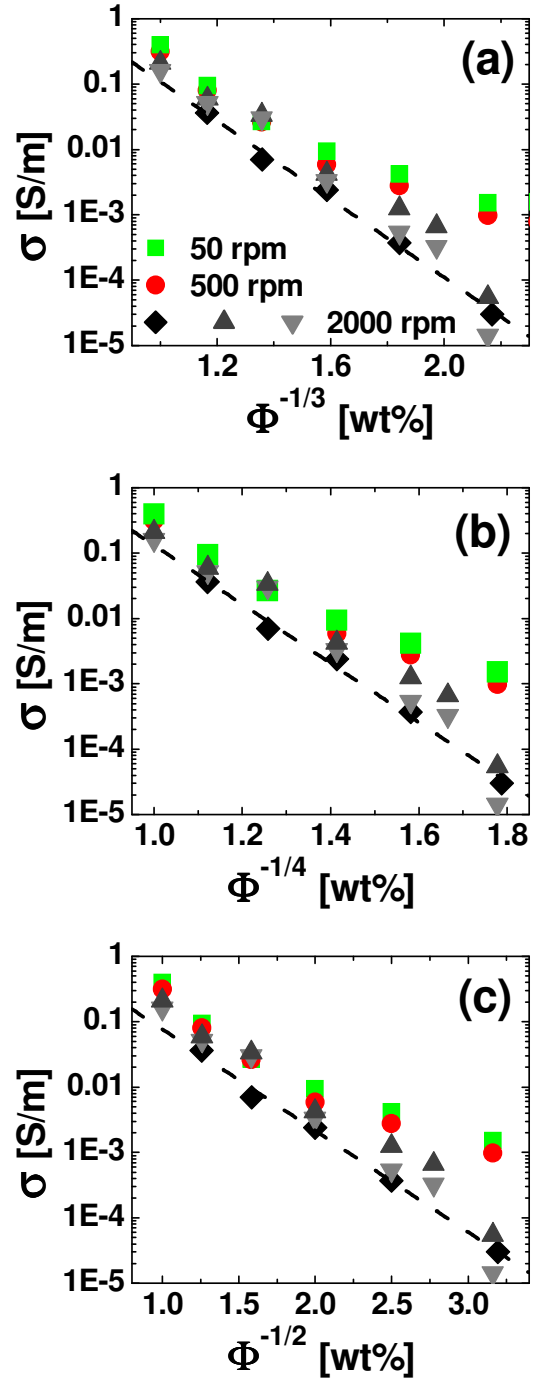$$<V_{ex}> \approx W L^2 \pi / 2$$



Fig. 6. Plot of the conductivity data from Fig. 2. as a function of (a) $\Phi^{-1/3}$, (b) $\Phi^{-1/4}$ and (c) $\Phi^{-1/2}$.
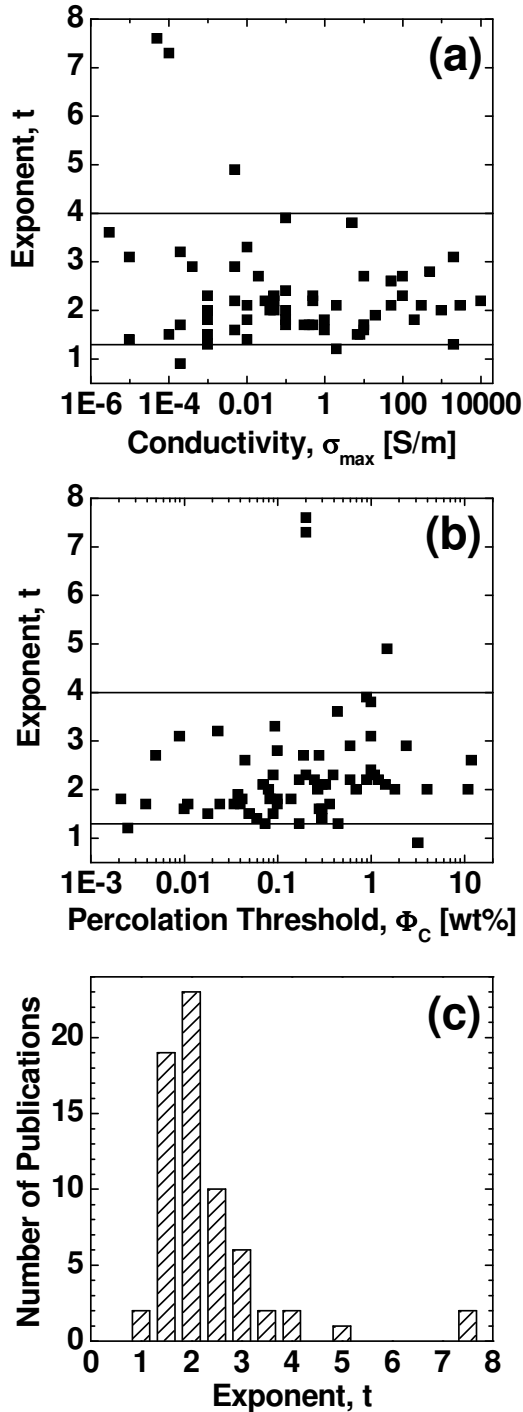
Fig. 7. Plot of the power law exponent t as a function of (a) the maximum conductivity and (b) the percolation threshold for all data in Table 1. The horizontal lines denote t = 1.3 and 4. Fig. 7 (c) shows a histogram of t values.

and

$$\Phi_C \sim V/\langle V_{ex}\rangle = W/(2L) = 1/(2\eta) \quad [5]$$

or

$$\Phi_C \approx 0.7/\eta \quad [11].$$

As already mentioned in Section 2, reported values for the statistical percolation threshold $\Phi_C$ agree very well with the above considerations.

From electron microscopy it became evident that CNT embedded in a polymer matrix generally are curved or wavy rather than straight [25]. The effect of waviness on percolation has been addressed by a couple of authors using different theoretical approaches [26]-29]. They all find the obvious result that the percolation threshold increases with increasing waviness of the CNT. However, in all calculations the increase in $\Phi_C$ remains well below a factor of 2 which means that the effect of waviness can be considered as small in the context of Table 1.

Frequently, CNT are dispersed in form of bundles. The effect of bundles on percolation has been calculated by Grujicic et al. [30]. As expected, the percolation threshold increases with increasing bundle radius.

Statistical percolation theory predicts for the dependence of conductivity on filler concentration a scaling law of the form

$$\sigma = \sigma_0 \cdot (\Phi - \Phi_C)^t.$$

Usually, experimental results are fitted by plotting log σ vs log $(\Phi - \Phi_C)$ and incrementally varying $\Phi_C$ until the best linear fit is obtained [95]. The critical exponent t is expected to depend on the system dimensionality with calculated values of t ≈ 1.33 in two and t ≈ 2 in three dimensions [1,2]. A value of t ≈ 3 has been obtained for a Bethe lattice and within mean field theory whereas a value of t ≈ 2.5 has been derived within a continuum model, the "Swiss cheese model" [1], which simulates distributed bond strengths or contact resistances. Similar results have been achieved by Balberg [31] allowing a nonrandom distribution of voids in random void models of continuum percolation.

As shown in Fig. 7, fits to experimental data for CNT/polymer composites yield values of t predominantly in the range from 1.3 to 4 peaking around t = 2 (Fig. 7 c). The above mentioned theories relate increasing values of t to increasing tunneling barriers between the fillers which would lead to low maximum composite conductivities. As visible in Fig. 7 (a), such a dependency is not found in the evaluated publications. Experiments by Kovacs et al. [8] carried out with the same system suggest a change in t from low values (~ 1.7) in the case of low (kinetic) percolation thresholds to high values (~ 2.3) in the case of higher (statistical) percolation. Fig. 7 (b) however does not reflect such a relation between the percolation threshold and the magnitude of t.

It seems rather complicated to extract geometrical information about the CNT network from experimentally determined values of t. We believe that such a procedure is generally not justified. First of all, scaling is limited to a concentration range very close to the percolation threshold. However, this range of validity has not been examined in detail for CNT/polymer composites. In addition, the results of statistical percolation theory are derived for ideal systems which contain a homogeneous dispersion of identical particles. Due to the spread in CNT properties, i.e., length, diameter, chirality, entanglement and waviness, CNT/polymer composites are far away from being ideal systems. A further complication arises from the fact that low percolation thresholds are likely to be kinetically produced, which makes the application of statistical percolation theory questionable.

Modeling of kinetic percolation requires complex and time-consuming calculations. Rahatekar et al. [32] applied dissipative particle dynamics (DPD) to investigate the dynamic behavior of an assembly of oriented fibers suspended in a viscous medium. After establishing the structural arrangement the fiber network impedance was assessed using Monte Carlo simulations. In future work the effects of polydispersity in fiber properties, of electrostatic interaction of fibers, and of shear forces on percolation threshold shall be studied. Wescott et al. [33] used DPD simulations to investigate methods of controlling the assembly of percolating networks of CNT in thin films of block copolymer melts. For suitably chosen parameters the CNT were found to self-assemble. Finally, Tozzi et al. [34] employed particle-level simulations [35] to investigate the time evolution of the microstructure and the electrical conductivity of CNT suspensions in shear flow. The simulations allow control of numerous properties, including the matrix viscosity, nanotube aspect ratio, shape, flexibility, and interaction forces. All these approaches are important steps towards a better understanding of kinetic percolation.

## 5. Electric field induced CNT network formation

Martin et al. [36] have shown that the formation of CNT networks can be induced by the application of an external electric field. Thus, electric fields not only align CNT but also enhance the attractive forces between neighboring CNT. Figure 8 shows the formation of a CNT network induced by a DC field of 100 V/cm. The growth of the network starts at

the positive electrode indicating that CNT are negatively charged in an epoxy/amine hardener system. As has been shown for carbon black/epoxy composites the chemical nature of the hardener mainly determines the charge of the filler particles [37]. AC fields are more effective than DC fields in the sense that the conductivity of samples cured in an AC field is one order of magnitude higher than for DC fields. Compared with shear percolated composites the absolute conductivities of AC field percolated samples are still one order of magnitude lower. Conductivity anisotropies of more than $10^4$ have been obtained. Figure 9 shows that the conductivities of cured samples saturate as a function of field strength and as a function of filler concentration. We believe that the last mentioned observation is equivalent to the transition from kinetic to statistical percolation. When approaching statistical percolation the mobility of CNT is reduced and the effect of the electric field vanishes. The formation of *AC electric field induced aligned SWCNT percolative columns between electrodes* has also been observed by Park et al. in SWCNT/UDMA/HDDMA composites [38].
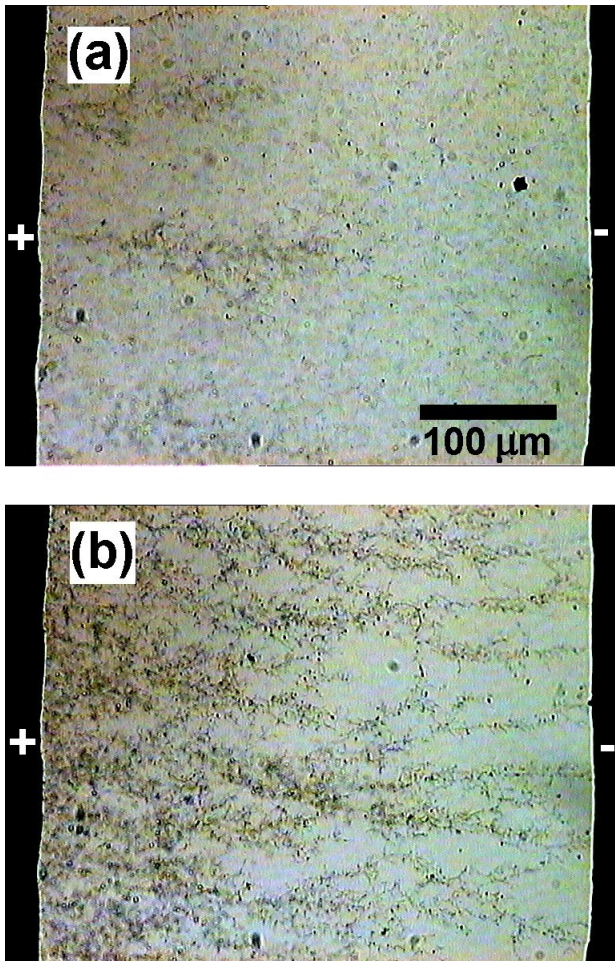


Fig. 8. Optical micrographs of a liquid epoxy composite containing 0.01 wt% MWCNT after 5 minutes (a) and 4 hours (b) of exposure to a 100 V/cm DC electric field at 80 °C. The scale bar is 100 μm.
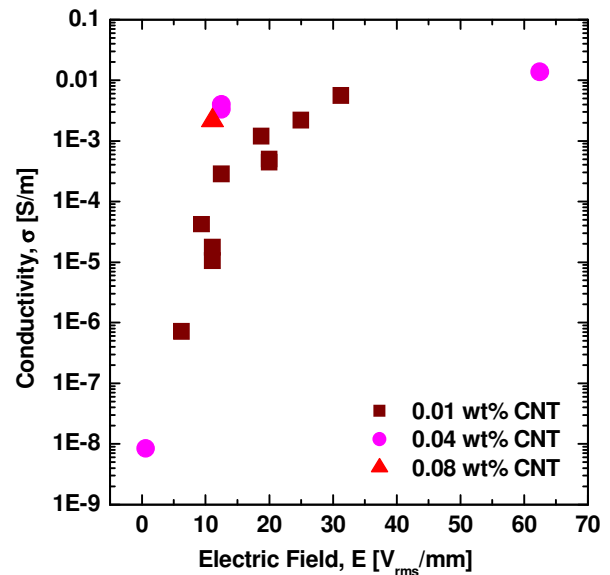


Fig. 9. Plot of the composite conductivity for various MWCNT concentrations after exposure to different AC field strengths during the curing time.

## 6. Conclusion

We reviewed 147 experimental results on electrical percolation of carbon nanotubes (CNT) in polymer composites published in 100 articles. The following conclusions can be drawn from these data:

(1) Referring to minimum percolation thresholds and maximum conductivities, type and production method of CNT seem to be less important than type of polymer and dispersion method.

(2) An indirect proportionality seems to exist between the percolation threshold and the maximally reached conductivity for given CNT concentrations and polymer matrices.

(3) Non-entangled MWCNT give conductivities 50 times higher than the usual entangled MWCNT from industrial mass production. Conductivity values below $\sigma = 500 \cdot \Phi^{2.7}$ S/m are indicative of polymer tunneling barriers between CNT.

(4) Many polymer composites seem to reproduce the theoretically predicted dependence of the percolation threshold on the aspect ratio $\Phi_C \approx 1/\eta$ once their filler particles are homogeneously distributed (statistical percolation).

(5) Deviating results with higher $\Phi_C$ suggest that the filler particles were not dispersed homogeneously, while lower $\Phi_C$ indicates the flocculation of homogeneously dispersed particles (kinetic percolation).

(6) Regarding the contradiction between the experimental results from Martin et al. [13] and the above mentioned theoretical prediction, we conclude that kinetic percolation cannot be described with statistical percolation theory.

(7) The magnitude of the percolation theory scaling law exponent t could not be related to any other parameter extracted from the articles. We believe that no reliable geometrical information about the CNT network can be extracted from most of the experimentally determined values of t.

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*Table 1. Summary of the experimental parameters of all reviewed publications, arranged alphabetically with respect to the polymer matrices, the data for a given polymer arranged with increasing percolation threshold.*

*Acronyms: ADA (aminododecanoic acid), AHA (aminohexanoic acid), AIBN (azoisobutyronitrile), APTS (aminopropyltriethoxy silane), ASTAA (alkoxysilane terminated amide acid), BKC (benzalkonium chloride), e (entangled), GA (gum arabic), MEK (methyl ethyl ketone), ne (non-entangled), OP (polyoxyethylene octyl phenyl ether), P3HT (poly 3-hexylthiophene), P3OT (poly 3-octylthiophene), PA-6 (polyamide-6), PANI (polyaniline), PAT (polyhexadecyl thiophene), PBT (polybutylene terephthalate), P(BuA) (polybutyl acrylate), PC (polycarbonate), PCL (polycaprolactone), PE (polyethylene), PEE (polyphenylene ethynylene), PEO (polyethylene oxide), PET (polyethylene terephthalate), PFA (polyfurfuryl alcohol), PI (polyimide), PMMA (polymethyl methacrylate), PmPV (poly-m-phenylenevinylene), PP (polypropylene), PPV (polyparaphenylene vinylene), PS (polystyrene), PU (polyurethane), PVA (polyvinyl acetate), PVC (polyvinyl chloride), PVDF (polyvinylidene difluoride), SDBS (sodium dodecylbenzenesulfonate), SDS (sodium dodecyl sulfate), SPPA (sulfonated polyphenylacetylene), UPR (unsaturated polyester resin), VE (vinylester), VMQ (methylvinyl silicone rubber).*

| Matrix | Filler | State | Treatment | d/l | Solution | Dispersion | $\Phi_C$ [wt%] | t | $\sigma_{max}$ [S/m] | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| ASTAA | SWCNT (HiPco®), Rice Univ. | e | HCl | - | C4H9NO | sonicated, stirred | 0.035 | - | 1E-7 @ 0.08 wt% | [39] |
| Epoxy | MWCNT (CVD) | ne | - | 200 | - | heat sheared | 0.0021 | 1.8 | 1E-3 @ 0.01 wt% | [13] |
| Epoxy | MWCNT (CVD) | ne | - | 340 | - | heat sheared | 0.0025 | 1.2 | 2E+0 @ 1 wt% | [6] |
| Epoxy | MWCNT (CVD) | ne | - | 1000 | - | heat sheared | 0.0025 | - | 4E-1 @ 0.5 wt% | [40] |
| Epoxy | MWCNT (CVD) | ne | - | 860 | - | heat sheared | 0.0039 | 1.7 | 2E-4 @ 0.01 wt% | [13] |
| Epoxy | SWCNT (Laser), Rice Univ. | e | purified | 400 | C6H8O | sonicated, cured without | 0.005 | 2.7 | 2E-2 @ 0.1 wt% | [7] |
| Epoxy | SWCNT (HiPco®), Carbon Nanotech. | e | purified | 150 | C6H8O | sonicated, cured without | 0.009 | 3.1 | 1E-5 @ 0.04 wt% | [7] |
| Epoxy | SWCNT (Laser), Rice Univ. | e | purified | 400 | C6H8O | sonicated, cured with | 0.01 | 1.6 | 5E-3 @ 0.4 wt% | [7] |
| Epoxy | MWCNT (CVD), Nanocyl | e | - | 1000 | - | stirred, heat sheared (slowly) | 0.011 | 1.7 | 4E-1 @ 1 wt% | [8] |
| Epoxy | SWCNT (HiPco®), Carbon Nanotech. | e | purified | 150 | C6H8O | sonicated, cured with | 0.023 | 3.2 | 2E-4 @ 0.2 wt% | [7] |
| Epoxy | MWCNT (CVD), Nanocyl | e | - | 1000 | - | stirred, heat sheared (medium) | 0.024 | 1.7 | 3E-1 @ 1 wt% | [8] |
| Epoxy | MWCNT (CVD), Hyperion Catalysis | e | - | 100 | C2H6O | sonicated, stirred | 0.03 | - | 5E-1 @ 0.15 wt% | [41] |
| Epoxy | MWCNT (CVD), Nanocyl | e | | 1000 | - | calendered, stirred | 0.03 | - | 1E-2 @ 0.3 wt% | [42] |
| Epoxy | MWCNT (CVD), Iljin Nanotech. | e | HNO3, centrifuged, C3H6O | 1000 | OP | sonicated | 0.034 | 1.7 | 1E-1 @ 2 wt% | [43] |
| Epoxy | SWCNT (Arc), Carbon Solutions Inc. | - | - | - | C3H6O | sonicated, stirred | 0.04 | 1.7 | 1E+1 @ 4 wt% | [44] |
| Epoxy | SWCNT (CVD), Thomas Swan | - | - | 1000 | - | calendered, stirred | 0.04 | - | 1E-3 @ 0.4 wt% | [42] |
| Epoxy | MWCNT (CVD), Iljin Nanotech. | e | H2O2/NH4OH, centrifuged, C3H6O | 1000 | OP | sonicated | 0.042 | 1.8 | 1E+0 @ 2 wt% | [43] |

| Epoxy | SWCNT (CVD), Thomas Swan | - | - | - | C2H6O, NaOH | sonicated, heat sheared | 0.05 | - | 3E-2 @ 0.5 wt% | [40] |
|---|---|---|---|---|---|---|---|---|---|---|
| Epoxy | SWCNT (Arc), Iljin Nanotech. | e | thermal oxidation, chemical treatment | 5000 | C2H6O | sonicated, vacuum pumped | 0.074 | 1.3 | 1E-3 @ 0.2 wt% | [45] |
| Epoxy | MWCNT (CVD), Nanocyl | e | - | 1000 | - | stirred, heat sheared (fast) | 0.08 | 2.0 | 4E-2 @ 0.6 wt% | [8] |
| Epoxy | SWCNT (CVD) | - | HCl | - | H2O | stirred | 0.08 | - | 2E-2 @ 0.4 wt% | [46] |
| Epoxy | SWCNT (HiPco®), Rice Univ. | e | HCl | - | - | sonicated | 0.1 | - | - | [47] |
| Epoxy | MWCNT (CVD), Iljin Nanotech. | e | - | 1000 | C3H6O | sonicated | 0.1 | - | 2E-1 @ 1 wt% | [48] |
| Epoxy | MWCNT, Nano Carbon Tech. | - | - | 100 | - | stirred | 0.1 | 1.8 | 1E-2 @ 0.12 wt% | [29] |
| Epoxy | DWCNT (CVD), Nanocyl | e | - | 1000 | - | calendered, stirred | 0.15 | - | 1E-2 @ 0.6 wt% | [42] |
| Epoxy | SWCNT (CVD), Thomas Swan | - | - | - | - | ball milled, heat sheared | 0.23 | - | 1E-3 @ 0.5 wt% | [40] |
| Epoxy | MWCNT (CVD), Nanocyl | e | NH2-functionalized | - | - | calendered, stirred | 0.25 | - | 5E-4 @ 0.4 wt% | [42] |
| Epoxy | DWCNT (CVD), Nanocyl | e | NH2-functionalized | - | - | calendered, stirred | 0.25 | - | 3E-4 @ 0.6 wt% | [42] |
| Epoxy | MWCNT (CVD), Iljin Nanotech. | e | UV/O3 | 1000 | C3H6O | sonicated | 0.27 | - | 2E-2 @ 1 wt% | [48] |
| Epoxy | SWCNT (HiPco®), Carbon Nanotech. | e | - | - | - | PMMA removal, Epoxy infiltration | 0.3 | - | 5E-1 @ 3 wt% | [49] |
| Epoxy | SWCNT (CVD) | - | - | - | C2H6O | sonicated, stirred | 0.3 | 1.4 | 1E-2 @ 2.5 wt% | [50] |
| Epoxy | MWCNT (CVD), Iljin Nanotech. | e | - | 1000 | | stirred | 0.4 | - | 2E-2 @ 1 wt% | [48] |
| Epoxy | MWCNT (CVD) | e | - | 400 | CH4O | stirred | 0.5 | - | 5E+0 @ 3 wt% | [12] |
| Epoxy | SWCNT (Arc), Aldrich | e | - | 1000 | - | manually mixed | 0.6 | - | 1E-2 @ 14 wt% | [51] |
| Epoxy | MWCNT (CVD), Shenzhen Nanotech. | e | - | 100 | C3H6O | stirred | 0.6 | 2.9 | 5E-3 @ 10 wt% | [52] |

| Epoxy | MWCNT (CVD) | - | - | > 500 | CH4O | stirred, hot pressed | 0.7 | - | 5E+0 @ 4 wt% | [53] |
|---|---|---|---|---|---|---|---|---|---|---|
| Epoxy | SWCNT (Arc), Carbon Solutions Inc. | e | HNO3 | - | C3H6O | sonicated, stirred | 1 | 2.4 | 1E-1 @ 7.5 wt% | [44] |
| Epoxy | MWCNT (CVD) | e | - | 80 | CH4O | stirred, filtrated | 1.5 | - | 1E-3 @ 3 wt% | [12] |
| Epoxy | MWCNT (CVD) | - | HNO3 | 20 | C3H6O | sonicated, stirred | 3.5 | - | 1E-5 @ 8 wt% | [54] |
| Epoxy | MWCNT (Arc), Aldrich | e | - | 100 | - | manually mixed | 4 | - | 1E-3 @ 16 wt% | [51] |
| Epoxy | MWCNT (CVD) | - | - | > 20 | C3H6O | sonicated, stirred | 5 | - | 2E-5 @ 20 wt% | [55] |
| Epoxy | MWCNT (CVD) | - | HNO3 | 20 | C3H6O, Tergitol | sonicated, stirred | 5 | - | 1E-5 @ 8 wt% | [54] |
| Epoxy | MWCNT (CVD), Arkema | e | - | - | - | calendered, vacuum stirred | < 0.5 | - | 3E-2 @ 2 wt% | [56] |
| P(BuA) latex | SWCNT (Arc) | e | PVA-functionalized | - | H2O | sonicated | 0.27 | - | 5E+0 @ 1 wt% | [57] |
| P3HT | MWCNT (CVD), Nanocyl | e | - | < 100 | CHCl3 | sonicated, CH4O (coagulation) | 0.1 | 1.7 | 5E-1 @ 20 wt% | [58] |
| P3OT | SWCNT (Arc), CarboLex | e | HCl, centrifuged | 100 | CHCl3 | sonicated, spincoated | 4 | 2.0 | 5E-2 @ 35 wt% | [59] |
| P3OT | SWCNT (Arc), CarboLex | e | - | 100 | CHCl3 | sonicated, spincoated | 11 | 2.0 | 1E-3 @ 35 wt% | [59] |
| PA-6 | MWCNT (CVD), Nanocyl | e | - | < 1000 | H2O, Na-AHA | sonicated, dried, extruded, hot pressed | 2.5 | - | 3E-2 @ 4 wt% | [60] |
| PA-6 | MWCNT (CVD), Hyperion Catalysis | e | - | - | - | extruded | 7 | - | 1E+1 @ 16 wt% | [61] |
| PANI | SWCNT (HiPco®), Carbon Nanotech. | e | - | - | - | sonicated | 0.3 | 2.1 | 3E+3 @ 15 wt% | [18] |
| PANI | SWCNT (HiPco®), Carbon Nanotech. | e | - | - | C8H10 | sonicated | 0.3 | 2.1 | 3E+2 @ 20 wt% | [18] |
| PANI | SWCNT (Laser), Carbon Nanotech. | e | - | - | C8H10 | sonicated | 0.3 | 2.1 | 3E+2 @ 20 wt% | [18] |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| PANI | MWCNT, Conyuan Biochem. Technology | - | - | 500 | - | blended, compressed | 4 | - | 1E+3 @ 80 wt% | [62] |
| PAT | MWCNT (CVD) | ne | HNO3, CHCl3 | > 200 | C6H12, CHCL3 | sonicated | 12 | 2.6 | 5E+1 @ 35 wt% | [63] |
| PBT | SWCNT (HiPco®), Carbon Nanotech. | e | oxidized | - | - | sonicated, extruded | 0.2 | - | 1E-8 @ 0.2 wt% | [64] |
| PC | SWCNT (HiPco®), Carbon Nanotech. | e | PEE-functionalized | - | CHCl3 | shaken, sonicated | 0.1 | 2.8 | 5E+2 @ 7 wt% | [65] |
| PC | SWCNT (HiPco®), Carbon Nanotech. | e | - | - | - | extruded | 0.3 | - | 1E-1 @ 1 wt% | [66] |
| PC | SWCNT (Arc) | e | - | - | C6H8O, CHCl3, C2H6O | sonicated, filtrated, hot pressed | 0.5 | - | 3E+1 @ 17 wt% | [67] |
| PC | SWCNT (HiPco®) | e | - | - | C6H8O, CHCl3, C2H6O | sonicated, filtrated, hot pressed | 0.5 | - | 1E+1 @ 1 wt% | [67] |
| PC | SWCNT (HiPco®) | e | - | - | - | extruded | 0.5 | - | 1E-1 @ 2 wt% | [67] |
| PC | MWCNT (CVD), Hyperion Catalysis | e | - | 1000 | - | extruded | 1 | 3.8 | 5E+0 @ 3 wt% | [68] |
| PC | MWCNT (CVD), Hyperion Catalysis | e | - | > 100 | - | extruded | 1.44 | 2.1 | 2E+0 @ 5 wt% | [69] |
| PC | SWCNT (Arc) | e | - | - | - | extruded | 1.9 | - | 1E-1 @ 10 wt% | [67] |
| PC | SWCNT (Arc) | e | - | - | CHCl3 | sonicated, extruded | 1.9 | - | 1E-1 @4 wt% | [67] |
| PC | SWCNT (Arc) | e | - | - | - | extruded | 2.5 | - | 1E-1 @ 7 wt% | [66] |
| PC | MWCNT (CVD) | e | HCl | 1000 | - | extruded | 5 | - | 1E-4 @ 15 wt% | [70] |
| PC | MWCNT (CVD), Hyperion Catalysis | e | - | > 100 | - | extruded | 1 - 2 | - | 1E+1 @ 15 wt% | [71] |
| PC | SWCNT (HiPco®), Carbon Nanotech. | e | annealed, SOCl2, centrifuged | - | - | extruded | - | - | 1E-1 @ 1 wt% | [66] |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| PC | SWCNT (Arc) | e | annealed, SOCl2, centrifuged | - | - | extruded | > 5 | - | 1E-1 @ 7 wt% | [66] |
| PCL | SWCNT (HiPco®), Carbon Nanotech. | e | purified | - | C7H8, ADA | sonicated | 0.09 | 1.5 | 1E-3 @ 3 wt% | [72] |
| PCL | MWCNT (CVD), Iljin Nanotech. | e | - | 1000 | - | sonicated, stirred | 1.5 | - | 1E+1 @ 7 wt% | [73] |
| PCL | MWCNT (CVD), Iljin Nanotech. | e | HNO3, filtrated | 1000 | - | sonicated, stirred | 4 | - | 1E+0 @ 7 wt% | [73] |
| PE, UHMW | MWCNT (CVD) | ne | - | 100 | H2O, SDS | sonicated, dry mixed, hot pressed | 0.045 | 2.6 | 5E+1 @ 1 wt% | [74] |
| PE, UHMW | MWCNT (CVD) | - | NaOH, HCl | > 100 | - | stirred, hot pressed | 0.07 | 2.1 | 1E-2 @ 0.7 wt% | [75] |
| PE, UHMW | SWCNT (Arc), CarboLex | e | - | - | C6H8O | sonicated, dry mixed, hot pressed | 0.09 | 2.3 | 5E-2 @ 2 wt% | [74] |
| PE, UHMW | MWCNT (CVD) | - | NaOH, HCl | > 100 | - | stirred | 0.14 | 1.8 | 1E-1 @ 0.7 wt% | [75] |
| PE, UHMW | MWCNT (CVD) | ne | - | 100 | C6H8O | sonicated, dry mixed, hot pressed | 0.19 | 2.7 | 1E+2 @ 1 wt% | [74] |
| PE, UHMW | SWCNT (Arc), CarboLex | e | - | - | C2H6O | sonicated, dry mixed, hot pressed | 0.25 | 2.2 | 5E-1 @ 3 wt% | [74] |
| PE, UHMW | MWCNT (CVD) | ne | - | 5000 | - | dry mixed, hot pressed | 0.28 | 2.7 | 1E+1 @ 1 wt% | [74] |
| PE, UHMW | SWCNT (Arc, high-grade) | e | - | - | - | dry mixed, hot pressed | 0.6 | 2.2 | 5E-2 @ 3 wt% | [74] |
| PE, UHMW | SWCNT (Arc, low-grade) | e | - | - | - | dry mixed, hot pressed | 1.1 | 2.3 | 5E-1 @ 3 wt% | [74] |
| PE, UHMW | SWCNT (Arc), CarboLex | e | - | - | - | dry mixed, hot pressed | 1.2 | 2.2 | 5E-3 @ 3 wt% | [74] |
| PE, LD | MWCNT (CVD) | e | HCl/HNO3, centrifuged | < 1000 | - | ball milled, hot pressed | 2 | - | 3E+0 @ 10 wt% | [76] |
| PE, HD | SWCNT (HiPco®), Carbon Nanotech. | e | purified | - | H2O, SDS | sonicated, centrifuged, sprayed, extruded | 4 | - | 5E-1 @ 6 wt% | [77] |
| PE, MD | MWCNT (CVD), Sun Nanotech | - | HCl | > 100 | - | extruded | 7.5 | - | 1E-2 @ 10 wt% | [78] |

| Polymer | CNT (synthesis), Supplier | | Treatment | | Solvent | Processing | | | Conductivity | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| PE, LD | MWCNT (CVD), Shenzhen Nanotech. | e | - | 100 | C8H10 | sonicated, melt mixed | 15 | - | 5E-6 @ 30 wt% | [79] |
| PEO | MWCNT (CVD), Nano-Lab | - | - | < 1000 | H2O, GA | sonicated, stirred, electrospinned | 0.45 | 1.3 | - | [80] |
| PEO | MWCNT (CVD) | - | HNO3 | - | C3H8O | stirred | 15 - 50 | - | 7E+2 @ 50 wt% | [81] |
| PET | SWCNT (Arc), CarboLex | e | - | 1000 | - | extruded, hot pressed | 0.7 | - | 1E-4 @ 2 wt% | [82] |
| PET | MWCNT (CVD), Shenzhen Nanotech. | e | HCl | 1000 | ODCB–C6H6O | sonicated | 0.9 | 2.2 | 3E-2 @ 9 wt% | [83] |
| PFA | MWCNT (CVD), Showa Denko K.K. | - | anneal | > 30 | - | sonicated, stirred, doctor blade | 8 | - | 1E+1 @ 15 wt% | [84] |
| PI | SWCNT (Laser), Rice Univ. | e | - | > 300 | C6H8O | sonicated, stirred | 0.05 | 1.5 | 1E-4 @ 1 wt% | [85] |
| PI | MWCNT (CVD), Hyperion Catalysis | e | - | 1000 | C4H9NO | sonicated, stirred | 0.3 | 1.6 | 1E+1 @ 7.4 wt% | [86] |
| PI | MWCNT (CVD), Sun Nanotech | - | H2SO4/HNO3, centrifuged | 100 | C4H9NO | sonicated | 9.5 | - | 2E-3 @ 12 wt% | [87] |
| PMMA | MWCNT (CVD) | ne | - | - | C8H18O4 | stirred, spincoated | 0.084 | 1.8 | 2E+2 @ 1 .5wt% | [88] |
| PMMA | MWCNT, NanoLab | - | - | 1000 | C2HF3O2, C4H8O | sonicated | 0.12 | - | 8E-1 @ 1.5 wt% | [89] |
| PMMA | SWCNT (HiPco®), Carbon Nanotech. | e | SOCl2 | - | CHCl3 | stirred | 0.17 | 2.2 | 1E+4 @ 10 wt% | [17] |
| PMMA | SWCNT (HiPco®), Carbon Nanotech. | e | - | - | CHCl3 | stirred | 0.17 | 1.3 | 2E+3 @ 10 wt% | [17] |
| PMMA | MWCNT (CVD), Iljin Nanotech. | e | - | - | C7H8 | sonicated, stirred | 0.2 | 2.3 | 1E+2 @ 10 wt% | [21] |
| PMMA | SWCNT (Arc) | e | - | - | C7H8 | sonicated | 0.33 | 2.1 | 5E+1 @ 8 wt% | [90] |
| PMMA | SWCNT (HiPco®), Rice Univ. | e | HCl, CH4O, annealed | 45 | C6H8O | sonicated, H2O (coagulation), hot pressed | 0.37 | - | 5E-2 @ 2 wt% | [14] |

| Polymer | CNT | | Treatment | | Solvent | Processing | | | Conductivity | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| PMMA | SWCNT (HiPco®), Rice Univ. | e | HCl | - | C6H8O | sonicated, H2O (coagulation), hot pressed | 0.39 | 2.3 | 1E-3 @ 2 wt% | [16] |
| PMMA | SWCNT (Arc) | e | HNO3 | > 1000 | C6H8O | sonicated, wet-stretched, hot pressed | 0.5 | - | 1E-1 @ 7 wt% (parallel) | [91] |
| PMMA | SWCNT (Arc) | e | HNO3 | > 1000 | C6H8O | sonicated, wet-stretched, hot pressed | 0.5 | - | 1E-5 @ 7 wt% (perp.) | [91] |
| PMMA | MWCNT, Aldrich | - | C6H8O, C2HF3O2, centrifugated | 100 | C2HF3O2, C4H8O | sonicated | 0.65 | - | 8E-2 @ 1.5 wt% | [89] |
| PMMA | SWCNT (Arc), CarboLex | e | - | - | H2O, SDS | sonicated, centrifuged, hot pressed | 0.7 | 2.0 | 1E-1 @ 1.5 wt% | [92] |
| PMMA | SWCNT (HiPco®), Rice Univ. | e | HCl, CH4O, annealed | - | C6H8O | sonicated, H2O (coagulation), hot pressed | 1.3 | - | 1E-2 @ 2 wt% | [93] |
| PMMA | SWCNT (HiPco®), Aldrich | e | SOCl2 | - | CHCl3 | shaken, sonicated | < 0.1 | - | 5E+1 @ 0.5 wt% | [94] |
| PmPV | MWCNT (Arc) | e | - | - | C7H8 | sonicated | 0.06 | 1.4 | 1E-5 @ 4 wt% | [95] |
| PmPV | MWCNT (Arc) | e | - | > 25 | C7H8 | sonicated | 7.5 | - | 2E-3 @ 35 wt% | [96] |
| PmPV | MWCNT (Arc) | e | - | - | C7H8 | sonicated, spincoated | 8 | - | 3E+0 @ 36 wt% | [3] |
| PP | MWCNT (CVD) | ne | - | 1000 | - | extruded | 0.07 | - | - | [97] |
| PP | MWCNT (CVD) | - | - | - | - | sonicated, extruded | 0.4 | - | 1E-1 @ 0.07 wt% | [98] |
| PP | MWCNT, Nanostr. and Amorph. Mat. Inc. | - | - | - | - | extruded (high shear), hot pressed | 0.44 | - | 2E+0 @ 9 wt% | [99] |
| PP | MWCNT (CVD), Iljin Nanotech. | e | H2SO4/HNO3, filtrated | 1000 | - | extruded, hot pressed | 1.5 | - | 2E-1 @ 5 wt% | [100] |
| PP | MWCNT (CVD) | - | HF, HCl | - | - | extruded, hot pressed | 2 | - | 5E-1 @ 10 wt% | [101] |

| Polymer | CNT | | Treatment | | Solvent | Processing | | | | Ref |
|---|---|---|---|---|---|---|---|---|---|---|
| PP | MWCNT, Nanostr. and Amorph. Mat. Inc. | - | - | - | - | extruded (low shear), hot pressed | 2.62 | - | 1E-4 @ 2.6 wt% | [99] |
| PPV | SWCNT (Laser) | e | - | - | - | sonicated | 1.8 | 2.0 | 1E+3 @ 64 wt% | [102] |
| PS | SWCNT (HiPco®), Carbon Nanotech. | e | PEE-functionalized | - | CHCl3 | shaken, sonicated | 0.05 | 1.5 | 7E+0 @ 7 wt% | [65] |
| PS | MWCNT (CVD), Arkema | e | - | < 60 | C6H8O | sonicated, stirred | 0.16 | - | - | [103] |
| PS | SWCNT (Arc), CarboLex | e | annealed | - | C6H4Cl2 | sonicated, stirred | 0.27 | 2.0 | 1E-3 @ 1 wt% | [104] |
| PS | SWCNT (Arc), CarboLex | e | - | - | H2O, SDS | sonicated, centrifuged, hot pressed | 0.28 | 1.6 | 1E+0 @ 1.5 wt% | [92] |
| PS | SWCNT (Arc), CarboLex | e | - | - | C6H4Cl2 | sonicated, stirred | 0.44 | 3.6 | 3E-6 @ 2 wt% | [104] |
| PS | MWCNT (CVD) | ne | - | 1000 | - | extruded | 0.45 | - | - | [97] |
| PS | MWCNT (CVD), Iljin Nanotech. | e | HNO3, HCl | - | - | sonicated | 0.8 | - | 1E-2 @ 2 wt% | [105] |
| PS | SWCNT (Arc), CarboLex | e | - | - | H2O, GA | sonicated, centrifuged, hot pressed | - | - | 1E-6 @ 3 wt% | [92] |
| PS | BMWCNT (Arc) | e | C3H6O, filtrated | - | C7H8 | sonicated, hot pressed | < 12 | - | 1E+4 @ 25 wt% | [106] |
| PS | MWCNT (Arc) | e | C3H6O, filtrated | - | C7H8 | sonicated, hot pressed | < 12 | - | 3E+2 @ 25 wt% | [106] |
| PS-Latex | SWCNT (CoMoCAT®), Soutwest Nanotech. | e | HF, filtrated | 2000 | H2O, AIBN, C5H8, SDBS, C16H34 | sonicated, stirred (miniemulsion) | 0.2 | 7.3 | 1E-4 @ 3 wt% | [107] |
| PS-Latex | SWCNT (CoMoCAT®), Soutwest Nanotech. | e | HF, filtrated | 2000 | H2O, AIBN, C5H8, SDBS | sonicated, stirred (macroemulsion) | 0.2 | 7.6 | 5E-5 @ 3 wt% | [107] |
| PS-Latex | MWCNT (CVD) | e | HNO3 | > 100 | H2O, SDBS | sonicated | 0.36 | 1.7 | 1E+1 @ 6 wt% | [108] |
| PS-Latex | MWCNT (CVD) | e | HNO3 | > 100 | H2O, SDBS | sonicated, freeze dried, hot pressed | 0.9 | 3.9 | 1E-1 @ 6 wt% | [108] |
| PS-Latex | SWCNT (Arc), CarboLex | e | - | 1000 | H2O, SDS | sonicated, centrifuged, hot pressed | 1.5 | 4.9 | 5E-3 @ 5 wt% | [109] |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| PS-Latex | MWCNT (CVD) | - | - | - | H2O, SDS | sonicated, centrifuged, stirred | 2.5 | - | 1E+1 @ 15 wt% | [110] |
| PU | MWCNT (CVD), Iljin Nanotech. | e | oxidized | 1000 | MEK, BKC | sonicated, stirred, calendered | 0.018 | 1.5 | 8E+0 @ 8 wt% | [111] |
| PU | MWCNT, Applied Science | - | - | > 100 | C4H8O | stirred | 1 | 3.1 | 2E+3 @ 15 wt% | [19] |
| PVA | MWCNT, Ahwahnee Techn. Inc. | ne | H2SO4/HNO3, filtrated | - | C6H8O | sonicated, stirred, electrospinned | 0.2 | - | 1E+1 @ 5 wt% | [112] |
| PVA | MWCNT (CVD), Hyperion Catalysis | e | H2SO4/HNO3, filtrated | - | H2O | stirred | < 10 | - | 1E+2 @ 60 wt% | [113] |
| PVA-Latex | SWCNT (HiPco®), Carbon Nanotech. | e | - | - | H2O, GA | sonicated, stirred, filtrated | 0.038 | 1.9 | 2E+1 @ 4 wt% | [114] |
| PVC | MWCNT (CVD), TMSpetsmash Ltd. | - | - | 1000 | - | stirred, grinded, hot pressed | 0.094 | 3.3 | 1E-2 @ 1.4 wt% | [115] |
| PVDF | SWCNT, Carbon Nanotech. | - | H2SO4 | > 1000 | C6H8O | spincoated | 0.02 | - | 3E-4 @ 0.05 wt% | [116] |
| PVDF | MWCNT | - | - | - | C6H8O | sonicated, hot pressed | 3.2 | 0.9 | 2E-4 @ 4 wt% | [117] |
| SPPA | MWCNT | - | - | - | - | sonicated | 3.5 | - | 2E-1 @ 20 wt% | [118] |
| UPR | MWCNT (CVD) | - | annealed | - | - | sonicated, magnetic field | < 1 | - | 1E-1 @ 1 wt% (parallel) | [119] |
| UPR | MWCNT (CVD) | - | annealed | - | - | sonicated, magnetic field | < 1 | - | 5E-3 @ 1 wt% (perp.) | [119] |
| VE | MWCNT (CVD) | - | NaOH, HCl, K2MnO4 | - | - | sonicated, stirred | < 0.5 | - | 4E-2 @ 2 wt% | [120] |
| VMQ | MWCNT | - | APTS-functionalized | 500 | - | hot pressed | 2.4 | 2.9 | 4E-4 @ 5 wt% | [121] |