Skoltech
Skolkovo Institute of Science and Technology

Thesis Changes Log

Name of Candidate: Biltu Mahato

PhD Program: Mathematics and Mechanics

Title of Thesis: Multifunctional interleaves for composite laminate

Supervisor: Dr. Sergey G. Abaimov (Supervisor – Skoltech)
Prof. Stepan V. Lomov (Co-supervisor – KU Leuven)

The thesis document includes the following changes in answer to the external review process.

Dear Jury Members,
I would like to thank all the jury members for taking the time to read my PhD dissertation and provide their constructive and valuable questions, comments, corrections, and suggestions. I have implemented the provided changes to improve my dissertation.
Below you will find my responses (in black) to the questions, comments, corrections, and suggestions provided by the jury members (in blue).

Sincerely,
Biltu Mahato

Reviews from Prof. Albert Nasibulin

The thesis is devoted to an important task of improvement of physical properties of polymer composites.
The thesis demonstrates a high quality of research and is well-structured. The abstract provides a clear overview of the research objectives and findings, while the introduction effectively sets the context for the study.
The methods used in the dissertation are highly relevant to addressing the problem of delamination in fiber reinforced polymer composites. The use of interlaminar region modification methods, such as interleaving polymeric veils and carbon nanotube interleave, shows promise in improving fracture toughness and introducing multifunctionality to the composite laminate.
The obtained results demonstrate scientific significance and align with the international level and current state of the art in the field of fiber reinforced polymer composites. The improvement in fracture toughness, electrical conductivity, and damage sensing capabilities of the laminates through the introduction of carbon nanotubes is in line with current research trends.
The obtained results have direct relevance to practical applications in various industries where fiber reinforced polymer composites are used. The enhanced fracture toughness, electrical conductivity, and damage sensing capabilities of the laminates offer potential for improved structural health monitoring and cure monitoring in composite manufacturing.
Further investigation is needed to understand the optimal concentration of carbon nanotubes in the interleave to achieve the desired balance between fracture toughness improvement and electrical conductivity. The scalability of the proposed methods should be explored to assess their

feasibility for large composite structures in industries such as aerospace. Additional validation and testing are required to assess the long-term durability and performance of the modified laminates in real-world applications.
Overall, the thesis presents a strong contribution to the field of fiber reinforced polymer composites, addressing the challenges of delamination and introducing multifunctionality to enhance the properties and functionalities of the laminates.

Thank you, Prof. Albert Nasibulin, for your positive evaluation of my PhD dissertation. I have implemented all the changes recommended by you as following:

Some questions and minor comments:

1. Pages 21-25: Lists of Figures and Tables should be removed. This is old style.

Response: Removed.

2. Page 29: "Masterbatch is the concentrated form of nanofillers which are produced to ensure that the nanofillers in dry form are mixed uniformly with the polymer and mixing consistency is maintained throughout the material. These masterbatches offer several advantages over the conventional dry form of nanofillers. Some advantages are as; High quality: Masterbatch provides mixing uniformity and consistency, ensuring high-quality dispersion." – can citations please be provided where a comparison in dispersion degree is shown? Masterbatches generally create areas of high viscosity which are hard agglomerates, how do they help in dispersion?

Response: To produce an isotropic nanocomposite, there are three methods of introducing nanofillers like CNTs in the matrix like epoxy as

a. Dry form: Introducing nanofillers in dry form has limitations like agglomeration of nanofillers in their dry form, hard agglomerates in the epoxy, and handling dry form of nanofillers have their linked health concerns. Good quality dispersion is possible with powerful techniques like three-roll milling which is expensive and not easily available at small-scale labs like ours.
b. Solvent form: The dry form of nanofillers is dispersed in a solvent. It stops the agglomeration of nanofillers in their dry form but suffers from the problem of re-agglomeration in the solvent after storage for some time.
c. Masterbatch: Dry/Solvent form of nanofillers are pre-dispersed in the epoxy matrix using multi-step three-roll milling which breaks the agglomeration of nanofillers in their dry form and hard agglomerates in the epoxy. Usually, it is in high viscous semi-solid form, so re-agglomeration will take a very long time compared to solvent form.

Following general practice, dispersion of 1D CNT-like nanofillers in a small laboratory is typically provided by shear mixing with agglomerates still present after dispersion. More energetic dispersion with, e.g., homogenization or ultrasonication threatens to damage nanofillers, especially SWCNTs. On the contrary, three-roll milling at expensive equipment in the industry guarantees good dispersion by the micrometer distance between rolls, simultaneously well preserving the nanofillers. So, using masterbatch instead of the other two methods gives a higher chance of getting a good quality dispersion because it is produced by three-roll milling. Moreover, it is simply a dilution of a concentrated pre-dispersed form. Ma et. al. concluded the pre-dispersion of nanofillers like CNT in a solvent followed by mixing in monomer/polymer to be an effective way to achieve relatively uniform CNT dispersion in nanocomposites [1]. Section 3.4.1 and Section 4.3.1 discuss the quality of dispersion in the nanocomposites.

The above assertion on masterbatch (as quoted in the question) is made for a comparative easiness of diluting the masterbatch by shear mixing compared to the dispersion of the conventional dry form of CNT. The text is corrected to give the comparative sense in its bullet point as “Some advantages are as; High quality: Masterbatch provides easier mixing to get uniformity and consistency, ensuring high-quality dispersion compared to dry form.”

3.
   a. Section 3.1, page 83 – why were 0.6% and 7.5% by weight chosen? These values are drastically apart, and no background is provided as to their selection.

Response: This research aimed to make sensors in which sensorial readings can be measured by a simple multimeter available in a lab. Nanocomposite containing 0.6 wt% SWCNT shows an electrical resistivity of ~30 Ω cm (Figure 4.4 – at the end of the cure cycle). The reference of 0.6 wt% was taken from Butt et. al. [2] who reported an electrical resistivity of 100 Ω cm for nanocomposite produced from the same masterbatch and mixing method at 0.5 wt% of SWCNT. A higher wt% may give even lower electrical resistivity but it would increase the viscosity of the mixture, making it difficult to process with a mechanical mixer. Hence, 0.6 wt% was finally selected as the fraction with the practice well established in the lab.
Similarly, the SWCNT wt% in masterbatch is 10 wt% and contains epoxy and SWCNT. For solidification, a compatible hardener must be added to the masterbatch. Upon adding hardener, the overall SWCNT wt% decreases to ~7.5 wt%. Considering the mixing ratio of epoxy and hardener, their weights in the final mixture were adjusted slightly to reach exactly 7.5 wt%. Hence, masterbatch concentration was chosen as another well-dispersed available-for-use material, shelf-ready for comparative analysis.

   b. Initial experimentation for the electrospun veils was with MWCNTs, here there is a switch to SWCNTs – why?

Response: This research aimed to make an inexpensive sensor in which sensorial readings can be measured by a simple multimeter available in a lab. So, in the beginning, a comparatively cheaper MWCNT was selected for the electrospun veil. The desired electrically conductive veil could not be produced even at the high wt% of MWCNT. Hence, in later research, MWCNT was replaced by more conductive SWCNT. Besides, market availability on the industrial scale of SWCNT well-dispersed masterbatches played its role in the choice, targeting future scalability in the industry.

4. Figure 3.8 – The thickness of the interleaves is much larger than 30 μm from the images. These values should be rechecked in Table 3.5.

Response: The thickness of the interleaves is 200-250 μm as mentioned in Section 3.4.2 and Table 3.5.

5. Chapter 3.2.3: how was pressure and heating applied during the curing cycle variation?

Response: The pressure and heat were applied by the metallic plates in the pressing machine. This detail is added in Section 3.2.2. A schematic diagram showing an application of pressure and heat in the pressing machine is also added in Figure 3.1c.

<u>Reviews from Prof. Dmitry Kolomenskiy</u>

The thesis explores the possibility to modulate properties of composite laminates by adding carbon nanotubes. It contains five chapters. The first and the last chapters are, respectively, the introduction and the conclusion; original results are contained in chapters 2, 3 and 4. Although chapter 2 is essentially a review of state-of-the-art electrospun polymeric interleave manufacturing technologies, it contains original results of areal density and conductivity tests obtained by the author of the thesis. Chapter 3 focuses on manufacturing and mechanical characterization of carbon nanotube masterbatch interleaves, chapter 4 concerns electrical conductivity properties, and these two chapters mainly contain new results obtained by the author. The thesis is well written and well structured.

The topic of the thesis as stated in the title is broad, but it embraces the actual contents. The manufacturing methods and the measurement methods are adequately chosen, allowing us to produce materials with the desired properties and to quantify those properties. The author has convincingly explained the scientific significance of the results by placing them in the context of the state-of-the-art international research activities. A possible industrial application is proposed in chapter 5, it concerns monitoring cure status of composite materials that use thermoset polymers. The results are published in peer-reviewed journals.

Thank you, Prof. Dmitry Kolomenskiy, for your positive evaluation of my PhD dissertation. I have implemented all the changes recommended by you as following:

Minor issues:

1. ‘Mode I’ is mentioned for the first time on page 34 without any explanation. The author should define the two modes, Mode I and Mode II, in the introduction.

Response: All three modes of fracture by delamination are defined briefly in Section 1.2.1.

2. Page 18: ‘Initiation’ and ‘propagation’ are not physical quantities per se measured in J/m^2. Are G1i, G1p, G2i and G2p surface energies?

Response: Indeed, G1i, G1p, G2i, and G2p are surface energy per unit fractured surface area which is also known as energy release rate in fracture mechanics.
Indeed, initiation and propagation are not physical quantities per se but just denote two events of crack initiation and propagation during the damage of material/structure by crack evolution.

3. Equation (4.3): Specifically, what kind of function is f? Is it known? Can the author plot it?

Response: f in Equation (4.3) is a complex algebraic exponential function. Yes, it is known and modeled in the theoretical work of our group and published in [3]. Modeling is outside the scope of this dissertation which is focused on experimental work. Hence, it is not included in this dissertation.

4. Equation (4.4) should be split in two: one with the ‘<’ and the other with the ‘>’ signs. Same with equation (4.5).

Response: Corrected as suggested.

5. The above issues are not critical. The thesis can be defended.

Response: Thank you for your positive evaluation of my dissertation.

Reviews from Prof. Dmitry Krasnikov

The thesis submitted by Mr. Biltu Mahato contains 161 pages and is written interestingly, i.e., contains an introduction to set the scene and the goal, a concise but reliable background review followed by three chapters with their own “experimental sections”. Though this choice provides extra deep involvement in the topic flow, there is another side of the coin – the continuity of the whole thesis might be affected.
The relevance of the research is supported not only by publications in leading journals of the field (e.g., Composites Science and Technology) but also the ever-growing implementation of more sophisticated composite materials. It should be stressed that, even in such a highly competitive field, the author was able to show a high level of results interesting for both fundamental and applied science. The hypotheses proposed must be confirmed with structural, mechanical, and microscopy methods used.
The integrity of the work is supported not only by the results of independent methods but also by the level of the journals and the conferences that indirectly verify the importance of the findings.

The author also indirectly shows his expertise in the outlook section to enlighten the pathway for future endeavors.

Thank you, Prof. Dmitry Krasnikov, for your positive evaluation of my PhD dissertation. I have implemented all the changes recommended by you as following:

The following comments should be addressed prior the publishing.

1. Carbon nanotubes are a wide family of materials. Should the author describe the following: How, for example, the number of walls or nanotube defectiveness might affect the properties of the final composite?

Response: Indeed, carbon nanotubes are a wide family of materials. For example,

a. Chirality: Changes in the orientation of carbon lattice in the CNT give rise to different forms of CNT like zigzag, chiral, and armchair. Their electrical conductivity varies from metallic to semiconductor range.
b. Number of walls: Single-walled CNTs have higher electrical conductivity than multi-walled CNTs at the same wt% merely by finer nanofillers and, thereby, stronger percolating networks. Other multiple factors have their influence too, but the higher number of nanofillers for SWCNTs at the same wt% is the prevailing factor.
c. Defects: Defects on the CNT wall are very common even for the highest quality CNTs. Ideally, the mean free path of an electron is comparable to the size of CNT hence for a defect-free CNT the highest electrical conductivity also known as ballistic conductivity is possible. However, such defect-free CNT is not possible to manufacture massively.

So, any change in the orientation of carbon lattice, number of walls, or defects on CNT will change its intrinsic electrical conductivity leading to a change in the overall electrical conductivity of the final composite.

2. Section 3.1 shows that three-roll milling was used to make the masterbatches at 10% by weight. This is because, at such high loading, the material becomes a solid and requires such advanced techniques. How was 7.5% by weight achieved by such simple procedures? What was the viscosity rating of the mixer and the 7.5% "interlayer"?

Response: The SWCNT wt% in masterbatch is 10 wt% and contains epoxy and SWCNT. For solidification, a compatible hardener must be added to the masterbatch. Upon adding hardener, the overall SWCNT wt% decreases to ~7.5 wt%. Considering the mixing ratio of epoxy and hardener, their weights in the final mixture were adjusted slightly to reach exactly 7.5 wt%. During mixing, acetone was also added as detailed in Table 3.4 which was later evaporated during the resting phase in the fabrication of composite laminate as detailed in Section 3.2.2. Upon adding acetone, the viscosity of the mixture decreases drastically easing the mixing process. The viscosity was not measured.

3. Chapter 3.2.1 – shows that CNTs are dispersed in a matrix and the resultant nanocomposite matrix is then applied as a layer – why is this called an interlayer when it is a surface modification of the fiber reinforcements rather than a free-standing structure? In essence, CNTs are just painted onto the surface.

Response: Indeed, it is an additional layer in between the plies in the laminate. That is why it is called interleave as defined in Section 1.1. In this research, the prepreg plies are used so it can't be considered as fiber modification because, in the prepreg, the reinforcing fiber is already impregnated with the matrix. So, in the final laminate, the nanocomposite layer sits as a distinct additional layer in between plies as seen in Figure 3.8. Hence, it is called an interleave.

4. For Figure 4.7 – how many isothermal and dynamic DSC scans were conducted to make such a smooth curve? They should be presented in the appendix section so that it is clear if the CNT interleaves influence the reaction kinetics and dynamics. Was there any signal-to-noise processing?

Response: Usually, 3-5 independent experiments were performed for the plotted data. For these DSC experiments, a high-frequency data collection (one data point each 0.3 sec) was used which provided large enough data for smooth curves. Data processing applied to the raw DSC data is added in Appendix A.

5. Page 31: "However, they suffer from poor out-of-plane properties because interlaminar fracture toughness (FT) is provided, besides matrix, only by the partial fibrous involvement in the form of the fiber-bridging effect." The sentence is unclear and possibly self-contradictory. Please comment.

Response: The sentence is corrected as "however, they suffer from poor out-of-plane properties because interlaminar fracture toughness (FT) is provided by matrix and only a partial fibrous involvement in the form of the fiber-bridging effect".

<u>Reviews from Prof. Amit Rawal</u>

The Ph.D. thesis entitled "Multifunctional Interleaves for Composite Laminate" has been evaluated. The novelty of the research has been effectively showcased through the design and creation of multifunctional laminates. This has been achieved by incorporating carbon nanotubes (CNTs) as interleaves in electrospun materials, improving Mode I fracture toughness and enhancing electrical conductivity. The ability of interleaved laminate to monitor the damage condition suitable for structural health monitoring applications has also been successfully demonstrated. The ability of CNTs dispersed in thermoset polymer has been investigated from an application perspective of multifunctional laminates. It has been found that a degree of cure exceeding 90% is essential for ensuring high strength. Therefore, closely monitoring the progression of cure development during composite manufacturing is deemed crucial.
Irrefutably, the research topic has undergone thorough investigation, making a substantial contribution to the current body of literature on electrospun and carbon nanotube materials. The PhD candidate has authored three journal articles, presented his work at numerous international conferences, and secured a patent, demonstrating the practical applications of the research work. There are a few grammatical and English errors that need to be addressed. In addition, the thesis needs to address the following **minor** corrections before the PhD degree can be awarded.

Thank you, Prof. Amit Rawal, for your positive evaluation of my PhD dissertation. I have implemented all the changes recommended by you as following:

1. Although the PhD candidate highlighted the novelty of the research work in several chapters, motivation/novelty must be added as a separate section in the Introduction.

Response: Motivation is present in Section 1.1. Novelty is added in Section 1.4.

2. A section dealing with clear-cut research objectives must be added to the thesis.

Response: The research objective is added in Section 1.3.

3. Page no. 29, it should be "Such agglomeration…mechanical and functional properties…."

Response: Corrected.

4. 'Non-woven' should be replaced by 'Nonwoven' throughout the thesis.

Response: Corrected.

5. Although there is a list of acronyms in the thesis, it is better to clearly define them within the text.

Response: Description added at the place where acronyms appeared for the first time.

6. The caption of Figure 2.3 has some typographical errors, please correct it.

Response: Figure caption corrected.

7. Fibre diameter and, if possible, fibre orientation distribution of electrospun materials can be provided in the thesis.

Response: These details are added in Section 2.5.2.

8. In the abstract, it is important to highlight whether SWCNTs or MWCNTs have been used in the research work.

Response: Corrected. Instead of using CNT as a general term, SWCNT and MWCNT are highlighted separately in the abstract to match the dissertation.

9. Please rationalize your results for the determination of fibre volume fraction in laminates, which are poorly cured.

Response: The overall thickness and thus the fiber volume fraction of the plates manufactured in compression molding depends on the pressure applied rather than the heating delivered during its production. The goal was to reach a fiber volume fraction of ~60% as desired in the aerospace industry. Hence, even for poorly cured plates, the overall thickness of plates is measured so that the fiber volume fraction against applied pressure in compression molding can be measured.

10. In Figure 3.11, there appears to be a discrepancy between the nature of force-displacement curves and the corresponding change in electrical resistance. Please justify. How many specimens exhibit this behavior? What is the value of R2 in Figure 3.12?

Response: Figure 3.11a is for LC interleaved and Figure 3.11b is for HC interleaved laminates in comparison to baseline laminate. Figure 3.11c is just the magnification of Figure 3.11a without a baseline to show correspondence between the drop in force and the stepwise rise in resistance. It is explained in detail in Section 3.4.5.
3-5 successful tests were carried out for each case. R^2 is added in the Figure 3.11 label for both cases.

11. A number of equations appear on page 129; kindly consider rationalizing them and providing clear definitions for their symbols.

Response: The physical description and symbol definitions of equations are present in Section 4.2.3.

<u>Reviews from Prof. Qiang Liu</u>

This thesis has tried two types of modifications based on CNTs to fabricate the multifunctional laminates. The first modification is interleaving the polymeric veil produced by electrospinning of polymers, but it cannot achieve electrically conductive laminates. The second one is CNT interleave by diluting CNT masterbatch, which can exhibit good improvements on the mode I fracture toughness and electrical conductivity. The author gives detailed analysis of the mechanically toughening and electrically conductive mechanisms induced by CNTs, and further demonstrates the potential applications on damage sensing and in-situ cure monitoring. The author has published multiple journal publications, conference papers and patents, and I think these good publications have demonstrated the scientific importance of this thesis.

Thank you, Prof. Qiang Liu, for your positive evaluation of my PhD dissertation. I have implemented all the changes recommended by you as following:

Other comments on this thesis are listed as follows,

1. In several places in thesis, there are typing errors of punctuation. For example, full stop is missing before 'since' on Page 72; semicolon is missing before 'hence' on Page 78; full stop

is not necessary after 5 °C/min on Pages 127 and 135. Please also check other parts of this thesis to avoid similar errors.

Response: Corrected.

2. In Chapter 2,

(a) SEM images from Figure 2.6 to Figure 2.10 show the PAN veil of different contents of CNTs. It is better to mark the PAN nanofiber and CNTs in the images so that the reader can understand the effects of CNT additions on the network structure.

Response: Unfortunately, the available SEM images do not allow us to distinguish nanofiber constituents. This detail is added in Section 2.5.2. Taking into account that veils were produced in Hungary (as detailed in Section 2.5), under current circumstances it is impossible to obtain them for any further studies.

(b) Figure 2.11 is not mentioned in the text.

Response: Added in Section 2.5.3.

(c) The effects of CNT content on the areal density of CNT-modified PAN veil are not clear. An explanation would be given.

Response: The areal density of the veil depends on the time of collection of nanofibers on an electrospinning drum (keeping manufacturing conditions constant - as noted by the same fiber diameter of ~200-500 nm measured on the SEM images as mentioned in Section 2.5.2). The time of collection of nanofibers was 15 min for all solutions irrespective of CNT wt%, as noted in Section 2.5.1. So, the areal density is expected to be the same for all cases. Areal density was measured as described in Section 2.5.3 and plotted in Figure 2.11. It is found to be almost the same for all cases as expected. This explanation is added in Section 2.5.3 for clarity.

(d) In equations 2.2 to 2.5, some parameters like R are not defined, although the read can guess its physical representation.

Response: Added.

(e) In trial 2, the length unit is cm, but it is mm in other parts. The same length units would be used in the whole thesis.

Response: Corrected to maintain uniformity.

3. In Chapter 3,

(a) for the HC interleaved laminates, the author mentions the lower part of the laminates has a smaller thickness than the upper part. A quantitative comparison is better to be given. The DCB tests show that interleaved CNTs lead to 27% and 0.5% improvement of initial and propagated mode I fracture toughness, respectively. For the former, are the results affected by the unsymmetrical thickness of the HC laminate? The author would give some comments.

Response: The thickness of both the upper and lower parts of laminates containing the fiber-reinforced part was equal as both had $[0]_8$ prepregs. However, in the interleaved laminates (both HC and LC), the thickness of the split of interleave was not always symmetric. Such unsymmetric thickness would affect the resistance calculations if it were calculated using Equation (3.5). But in this research, Equation (3.5) was modified by replacing the dependent terms (thickness, resistivity, etc.) with independent terms (L_o, R_o, etc.) as given by Equation (3.6). This was further deduced to get Equation (3.7) which only depends on the effective length of the arms. It is detailed in Section 3.3.4.

Similarly, for Mode I fracture toughness, only the modified compliance calibration (MCC) method of data reduction depends on the thickness of the overall sample instead of individual arms as detailed in Section 3.3.3 and Equation (3.2) – Equation (3.4). So, unsymmetrical thickness does not affect fracture toughness calculations. Moreover, the fracture toughness for comparison was calculated by the modified beam theory (MBT) data reduction method which is independent of the thickness.

(b) The author mentions several types of toughening mechanisms induced by CNTs, which are believed to have positive contributions to the initial mode I fracture toughness. Why do these toughening mechanisms not have a similar contribution to the propagation fracture toughness?

Response: The propagation fracture toughness value reported is an average value which shows a small improvement over the baseline. If comparison over the time interval leading to the full failure of the sample is considered, as shown in Figure 3.10 in the R-curve, it can be noted that the propagation energy is also higher at the beginning after the initiation. It drops only later after the crack becomes very long, possibly because the toughening mechanism was not effective in resisting crack propagation at such a large scale. Besides, crack propagation in some samples tended to move the crack plane from the interleave into the adjacent ply which may indicate that propagation energy may be underestimated.

(c) According to Figure 3.11(b), the peak load of HC laminates is almost equal to that of baseline laminates, which cannot demonstrate the improvement of initial mode I fracture toughness.

Response: In Figure 3.11(b), the first drop in the load (around ~45 N force) represents the crack initiation point which is lower than in the case of HC laminate (around ~50 N force).

4. In Chapter 4, as for the cure monitoring, it is better to give an example to demonstrate how to calculate the degree of curing when the overall resistance is obtained.

Response: Electrical resistance measurement and degree of cure calculation are two independent experiments. Electrical resistance measurement is performed when the samples are cured in the oven as detailed in Section 4.2.3 whereas the degree of cure is calculated from the heat of reaction measured in the differential scanning calorimeter as detailed in Section 4.2.5 and Equation (4.6).

<u>Other changes:</u>

- The second patent filed in China was published on Dec. 15, 2023. This information is updated in the List of Publication chapter and Section 4.6.
- The line spacing has been decreased to 1.5 to comply with the requirement for hardcopy printing.
- Texts are rearranged in some places to adjust figures.
- English is polished.

References:

[1] P.C. Ma, N.A. Siddiqui, G. Marom, J.K. Kim, Dispersion and functionalization of carbon nanotubes for polymer-based nanocomposites: A review, Compos Part A Appl Sci Manuf 41 (2010) 1345–1367. https://doi.org/10.1016/j.compositesa.2010.07.003.

[2] H.A. Butt, S. V. Lomov, I.S. Akhatov, S.G. Abaimov, Self-diagnostic carbon nanocomposites manufactured from industrial epoxy masterbatches, Compos Struct 259 (2021) 113244. https://doi.org/10.1016/j.compstruct.2020.113244.

[3] S. V. Lomov, N.A. Gudkov, S.G. Abaimov, Uncertainties in Electric Circuit Analysis of Anisotropic Electrical Conductivity and Piezoresistivity of Carbon Nanotube Nanocomposites, Polymers (Basel) 14 (2022) 4794. https://doi.org/10.3390/polym14224794.