RiESTech
Recent in Engineering Science and Technology
MBI

Article

Uneven Doping of Metal Powder in Carbon Polymer Composites Affects Electrical Conductivity Properties

Agus Edy Pramono [1,*], Iman Setyadi [1], Aminudin Zuhri [1], Anissa Puspa Dewi [1], Iwan Susanto [1], Tatun Hayatun Nufus [1], Nanik Indayaningsih [2]

[1] Magister Program in Applied Manufacturing Technology Engineering, Politeknik Negeri Jakarta, Jl. Prof. Dr. G.A. Siwabessy, Kampus UI, Depok 16425, Jawa Barat, Indonesia.
[2] Research Centre for Physics-National Research and Innovation Agency, Puspiptek Area, Gd. 440-442, South Tangerang, Banten 15310, Indonesia.
* Correspondence: agus.edypramono@mesin.pnj.ac.id

Abstract: This paper compares the electrical conductivity of LLDPE (Linear Low-Density Polyethylene)-carbon composite materials, LLDPE-carbon-aluminum composites, and LLDPE-carbon-copper composites. Doping with aluminum (Al) and copper (Cu) metal powders influences electrical conductivity in carbon-based polymer composite materials. Adding metal powders as secondary fillers to a mixture of conductive carbon powders and LLDPE can decrease electrical conductivity. This is due to the agglomeration or clustering of metal powders within the polymer matrix, which disrupts conductive pathways and diminishes the efficiency of electrical charge transfer. The impact of filler type and quantity on electrical conductivity in composite materials was examined, and the findings revealed that factors such as the filler's amount, shape, and dispersal significantly affect the composite's electrical resistance properties. Increasing the amount of metal powder filler raises the composite's viscosity, reducing adhesion between the metal and polymer fillers while promoting metal-to-metal contacts.

Keywords: Copper powder doping; Aluminum powder doping; Polymer composite; Electrical conductivity; LLDPE-carbon composite.

Citation:. Pramono, A. E., Setyadi, I., Zuhri, A., Dewi, A. P., Suswanto, I., Nufus, T. H., Indayaningsih, N. (2025). Uneven Doping of Metal Powder in Carbon Polymer Composites Affects Electrical Conductivity Properties. Recent in Engineering Science and Technology, 3(02), 1–14. Retrieved from https://www.mbi-journals.com/index.php/riestech/article/view/95

Academic Editor: Vika Rizkia

Received: 31 January 2025
Accepted: 16 April 2025
Published: 30 April 2025

Publisher's Note: MBI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2025 by the authors. Licensee MBI, Jakarta, Indonesia. This article is an open access article distributed under MBI license (https://mbi-journals.com/licenses/by/4.0/).

1. Introduction

This study reveals evidence that the addition of aluminum or copper metal increases the electrical conductivity of Linear Low-Density Polyethylene (LLDPE) polymer composites, but not significantly compared to electrically conductive carbon fillers.

This study focuses on developing conductive polymer composite (CPC) materials made from a blend of conductive organic carbon fillers as the primary filler and metal powders as the secondary filler (doping), integrated into a thermoplastic polymer matrix of LLDPE. The resulting hybrid composite combines three components to create a carbon-based material with enhanced mechanical properties and sufficient electrical conductivity to function as a raw material in electrical distribution systems. The hybrid composition improves the performance of both the fillers and the polymer matrix.

A few years ago, electrically conductive polymer-carbon composites were extensively researched. To improve the electrical conductivity properties of the polymer composite, some studies added metal powder mixed with conductive carbon powder.

Carbon fillers and metal powders enhance the composite's mechanical, functional, physical, chemical, and conductive properties, while LLDPE provides excellent thermoplastic performance. Incorporating 2% MWCNT (Multi-Walled Carbon Nanotubes) into the polymer-carbon black composite significantly improves the electrical conductivity of the carbon filler [1]. A hybrid carbon polymer composite consisting of LLDPE (92%), Polypyrrole/PPY (2%), and Graphene Nanoplatelet/GnP filler (6%) exhibits superior mechanical properties compared to a two-component LLDPE-GnP composite [2]. Hybrid composites are essentially modifications of two-component conductive polymer composites (CPCs). CPC materials can be fabricated by engineering thermoplastic polymers as the binding matrix mixed with conductive carbon fillers [3]. At a certain composition level, conductive carbon fillers are interconnected through interfacial bonding between carbon particles, forming a network of conductive channels through which electrons can flow, creating an electrical current [4]. Electrically conductive carbon allotropes are commonly used as fillers, yielding varying results. Carbon Black (CB) filler at loadings of 5%, 10%, 15%, and 20% within an LLDPE matrix enhances the surface hardness of the CB/LLDPE composite. However, tensile strength declines when filler loading exceeds 5% due to particle agglomeration, which impairs the transfer and distribution of tensile stress from the polymer chains to the clustered CB particles. Similarly, due to percolation effects, electrical conductivity decreases beyond 5% filler loading [5]. CNT (Carbon Nanotube) serves as a conductive filler in carbon polymer composites. SWCNT (Single-Walled Carbon Nanotube) with its single-layered structure has direct interaction with the polymer matrix, enhancing the mechanical properties and electrical conductivity of the composite [6]. MWCNT (Multiwalled Carbon Nanotube) is formed by several SWCNTs arranged in a complex matrix. This structure provides higher mechanical strength compared to SWCNTs. MWCNTs exhibit good resistance to pressure and strain, contributing to high load-bearing strength [7]. Graphite is used as a conductive filler in combination with various types of thermoplastic polymers such as ABS, PP, PE, and PET. This results in carbon polymer specimens with conductivity ranging from 0.71 to 5.0 S/cm at the temperatures used in the 3D printing filament manufacturing process [8]. The polymers used as matrices are quite effective in forming conductive channels, especially for non-polar polymers such as Polypropylene (PP), Polyethylene (PE), and Polyvinyl Chloride (PVC) [9]. This article explores the creation of cost-effective thermoplastic composite filaments for 3D printing. These filaments employ polypropylene (PP) as the polymer matrix and carbon black (CB) as the conductive filler. The composite demonstrates stable electrical properties and has been successfully utilized in 3D-printed applications such as plastic thermometers and flexible sensors [10]. In a related study, a Polycaprolactone (PCL) polymer matrix was successfully converted into an electrically conductive composite by incorporating 15% carbon black (CB) filler, which was subsequently processed using a 3D printing (3DP) machine. The PCL/CB composite was utilized to produce flexible sensors and 3D-printed gloves as demonstration applications. However, filler loadings exceeding 15% were found to hinder the 3D printing process, posing challenges in achieving consistent results [11]. This article examines polymer composites made from carbon black particles derived from apple wood shells. Higher carbonization temperatures and filler content improve the carbon content, tensile strength, and flexural strength of the composites. Scanning electron microscopy (SEM) analyzes the filler-matrix bonding [12]. This article examines polymer composites with nickel and copper fillers, offering metal-like electrical and plastic-like mechanical properties. Electrical conductivity follows percolation theory, while thermal conductivity is unaffected. Particle shape and packing factor are key to concentration dependence [13]. This study examines three types of fillers (Al, Fe, Cu) with varying particle shapes and sizes in HDPE. The relationship between filler percentage and the composite's tensile properties and electrical resistivity is explored. Tensile properties are influenced by filler shape, adhesion, and loading, while electrical resistivity depends on filler shape and amount. Young's modulus increases with higher filler content, following the typical trend in polymer composites [14]. The use of organic materials for conductive carbon has gained attention due to sustainability concerns. However, achieving optimal conductivity often requires high filler content, which can reduce toughness. Percolation theory shows that higher conductivity can be achieved by increasing filler quantity and improving its distribution [15]. A study with a 70/30 polymer/carbon composition achieved a conductivity of 9.09 S/m using carbon from palm fruit bunches. SEM revealed uniform carbon pore distribution in the longitudinal layers, with higher filler concentration in the lower vertical layers [16]. This research develops conductive polymers (CPs) by blending nylon with activated carbon. Electrical conductivity and activation energy were measured at different activated carbon mass fractions. Results showed conductivity increased from $5.62\times10^{-9} \pm 1.89\times10^{-10}$ S/cm in pure nylon to $2.51\times10^{-8} \pm 2.87\times10^{-10}$ S/cm with 8% activated carbon. Activation energy decreased as the carbon fraction increased [17]. This study characterizes PAni/carbon composites from candlenut shells as capacitor electrodes. Activated carbon was synthesized at various temperatures (300°C, 400°C, 500°C, and 600°C). Higher activation temperatures improved the composite's electrical conductivity, reaching a maximum of 5.7×10^{-3} S/m. The composite activated at 600°C had more and deeper pores, with the highest measured capacitance at 10.52 μF [18]. Conductive polymer composites (CPCs) are being developed to enhance electrical conductivity and mechanical properties. Metal powders are used as conductive fillers in CPCs. This research examines the melt flow rate (MFR) of an aluminum (Al) and ABS polymer composite with a 10% weight loading of Al filler. The results indicate an increase in MFR. This research holds potential for the production of lightweight and customizable conductive structures [19], improving the impact resistance [20]. At certain concentrations, it can reach a low percolation threshold to obtain a conductive material [21]. In PP-based conductive polymer composites (CPC) with carbon filler, copper enhances mechanical properties. Research using compounding, remixing, hot blending, and hot-pressing processes showed that adding copper with a conductivity of 5.80×10^{5} S/cm to the PP/C composite improved both conductivity and mechanical properties. Copper increased the composite's density, reduced porosity, and enhanced tensile strength, flexural strength, tensile modulus, flexural modulus, and elongation [22]. LLDPE polymer was used in this study because it is a suitable material for conducting polymer composites (CPC) due to its ease of processing at its recrystallization temperature and its non-polar nature [9,23]. Several studies have shown that LLDPE-based conductive polymer composites (CPC) incorporating nano-sized carbon allotropes can achieve very low percolation thresholds [6,8,24]. Significant advancements have been made in developing polymers with great potential as alternative materials across industries. For example, Polyetheretherketone (PEEK) can be used to create conductive polymer composites (CPC) with excellent mechanical properties, particularly in fatigue resistance and impact strength [25]. PEEK is a polymer with a very high processing temperature. Currently, there is no known development of composite materials using electrically conductive carbon fillers from organic materials in PEEK polymer. However, several composite materials have been introduced as industrial materials, fabricated and processed from various components or hybrids, with binders made from low-melting-point metal materials [26]. The research shows that the prototype Extruder Head effectively stabilizes composite density. Higher density resulted in a notable increase in electrical conductivity. These findings highlight the successful development of a CPC material with improved conductivity, making it ideal for high-carbon-loading composites [27]. The purpose of this study was to study the characteristics of physical properties and electrically conductive properties of composites fabricated from organic carbon materials (rice husks) and LLDPE [28]. This paper explores the electrical and mechanical properties of filament materials made from biomass-derived carbon particles in an LLDPE matrix. Filaments, slender threads or fibers, are used in various fields such as textiles, plastic manufacturing, and more, including 3D printing. The study aims to develop composites with electrically conductive carbon and LLDPE polymer to enhance electrical conductivity [29]. This article discusses the engineering of composite materials made from a mix of conductive organic carbon filler and LLDPE polymer. Conductive micro carbon from rice husks was incorporated into an LLDPE matrix using hot compaction. The composite varied in filler composition with carbon loadings of 50%, 45%, and 40%, and mesh sizes of #150, #200, and #250 [30].

This article presents an experiment on fabricating composite materials using LLDPE polymer as the binding matrix, enabling the formation process to occur at a low temperature for easy shaping. Electrically conductive carbon from abundant organic materials served as the primary filler, while aluminum (Al) and copper (Cu) metal powders were used as secondary fillers to create a hybrid composite.

2. Materials and Experiment Methods

Carbonization

Conductive carbon is made from rice husk filler through carbonization at 950°C, with a heating rate of 2°C per minute. The material is held at this temperature for 4 hours, then cooled naturally. The resulting conductive carbon is milled and sieved to obtain carbon particles with a mesh size of #200 (about 74 μm).

Metal powder filler

This study uses copper (Cu) and aluminum (Al) powders as conductive fillers, known for their high conductivity and use in electrical equipment manufacturing. The Cu powder has 99.90% purity, a mesh size of #200 (about 74 μm), a conductivity of 5.96×10^7 S/m, and a density of 8.96 g/cm^3. The Al powder has 96.00% purity, a mesh size of #300 (about 44 μm), a conductivity of 3.5×10^7 S/m, and a density of 2.70 g/cm^3, used in power distribution.

Thermoplastic LLDPE

The plastic resin used in this research is LLDPE (Linear Low-Density Polyethylene), specifically the ETILINAS LL3840UA grade. It has a white base color and a mesh size of #40 (approximately 400 μm). The resin's relative density to water ranges from 0.91 to 0.98, and its MFR (Melt Flow Rate) is 4 g/10 min. The polymer melts at 124°C, with crystallization occurring at 111°C.

Hot compaction

Heat compaction is carried out by a manual hydraulic machine with a power of 400 bar. The heat printing process is carried out at a pressure of gradually up to 100 bar while being heated on a controlled electric heater.

The composite samples were fabricated using a high-precision digital scale with weight fraction composition ratios. Five specimens were prepared for each ratio.

Table 1 shows the composition of LLDPE carbon composites without the addition of metal powder.

Table 1. Composition of carbon-LLDPE

Sample Code	HOA	HOB	HOC
LLDPE, % w	50	55	60
Carbon, % w	50	45	40
Metal doping, %w	0	0	0

Table 2 shows the composition of carbon-LLDPE composites with the addition of aluminum powder, and the composition of aluminum powders with LLDPE, with carbon.

Table 3 shows the composite composition of carbon-LLDPE with the addition of copper powder, and the composition of copper powder and LLDPE, with carbon.

Mixing all ingredients is done manually, compressing the heat gradually, and pressing at a gradual pressure. The pressure gradually reaches 100 bar and is lowered to 50 bar at an initial temperature of 90°C. The temperature of the compass is raised to 130°C and held for 20 minutes. The sample is degraded from the mold. The shape and dimensions of the electrical and physical properties of the test sample are 10 × 10 × 5 mm.

Table 2. Composition of Carbpn-LLDPE-Al powder

Sample code	HAA	HAB
LLDPE, %w	50	50
Carbon, %w	40	30
Al_powder, %w	10	20

Table 3. Composition of Carbon-LLDPE-Cu powder

Sample code	HCA	HCB
LLDPE, %w	50	50
Carbon, %w	40	30
Cu powder, %w	10	20

SEM-EDS testing

Carbon element and microstructure testing were conducted using the Hitachi SU 3500 SEM machine at the National Research and Innovation Agency (BRIN) Physics Laboratory in Serpong, Indonesia. Microscopic imaging uses the Secondary Electron (SE) and Backscattered Electron (BSE) techniques.

Electrical conductivity test

Electrical conductivity testing was conducted at the Physics Laboratory of the National Research and Innovation Agency (BRIN) in Serpong, Indonesia, following the ASTM D4496 standard. The four-point probe method used the Keithley Source Meter® 2450.

3. Results and Discussion

The composite specimens of only LLDPE and carbon, shown in Table 4, used homogeneous blends of LLDPE polymer and micro carbon filler from rice husk in ratios of 50:50, 55:45, and 60:40. These were used as a reference to measure the effect of adding metal powders to the carbon polymer composite.

The LLDPE-carbon composite specimens will be compared to the characterization of specimens using metal powder fillers as a substitute for conductive carbon. The specimens with aluminum powder fillers are coded as HAA, HAB, HAC, and HAD, while the specimens with copper powder fillers are coded as HCA, HCB, HCC, and HCD.

The specimens HOB and HOC also consist of a homogeneous mixture of LLDPE as the binding matrix and microcarbon conductive filler from rice husk but in different ratios. The code HOB is used for the composite with a composition of LLDPE: C (55:45), and the code HOC is used for the composite with a composition of LLDPE: C (60:40), referring to the codification in Table 4.

The results of electrical conductivity testing for conductive carbon loading are in Figure 1. Higher carbon content led to higher conductivity. The HOA composite with a 50:50 LLDPE: C ratio achieved the highest conductivity of 9.43E-04 S/cm. The HOC composite with a 60:40 LLDPE: C ratio had the lowest conductivity of 1.35E-04 S/cm. Lower carbon composition reduces the formation of conductive pathways, hindering electron flow within the composite.

Table 4. Sample code and composition ratio

Sample Code	HOA	HOB	HOC
LLDPE, % w	50	55	60
Carbon, % w	50	45	40
Metal doping, %w	0	0	0
Electrical Conductivities, S/cm	9.43E-04	3.47E-04	1.35E-04

The electrical conductivity performance can be supported by the conductive carbon reinforcement composition. Research shows that using a combination of several carbon allotropes in hybrid composites significantly enhances conductivity [22]. The very low conductivity is due to the high LLDPE matrix composition. Its insulating properties cause it to effectively insulate the carbon filler, hindering electricity flow in the HOC specimen. This is further supported by using PP as a polymer in hybrid composites without metal fillers [31]. The addition of carbon reinforcements successfully increased the electrical conductivity value of the hybrid composite based on PP polymer [22].

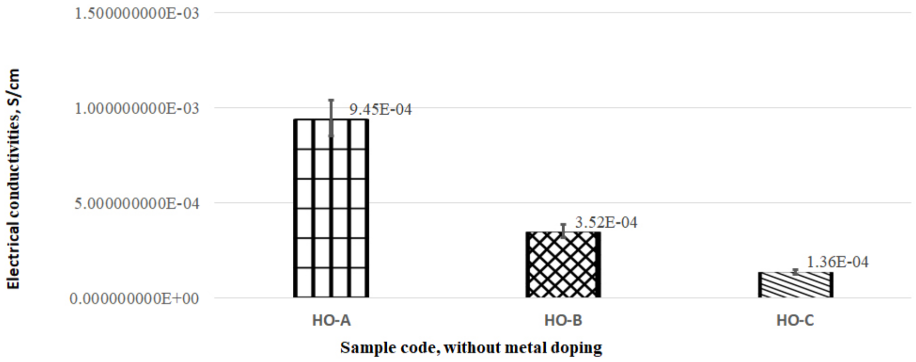

Figure 1. Electrical conductivity of LLDPE-carbon composite

During the initial mixing and compaction, conductive carbon particles aggregate within the polymer powder voids due to their smaller quantity and similar size to the voids. With increased heat, these particles absorb the molten polymer, forming a thin layer on their surfaces. The densely packed carbon clusters absorb the polymer layer initially and diffuse into the polymer as the molten polymer equilibrium changes.

Under certain conditions, carbon particles aggregate in the polymer voids, forming conductive channels that enhance the material's electrical conductivity. These interconnected carbon aggregates create pathways for electron flow. More conductive channels result in higher conductivity.

Electrical conductivity of metal filler LLDPE-carbon composite

To increase electrical, metal powders are added to the LLDPE/C carbon-polymer composite. This is done by replacing microcarbon weight with an equal weight of metal fillers like aluminum and copper powders, as metals are good conductors.

In the HAA specimen, 40% microcarbon and 10% aluminum powder by weight are used, matching the 50% total filler weight in the HOA specimen. This substitution is used to observe its effect on the hybrid composite's electrical conductivity.

Figure 2 shows the electrical conductivity graphs for LLDPE/C-Al and LLDPE/C-Cu hybrid composites. Substituting 10% conductive carbon with aluminum (HAA) and copper (HCA) did not improve conductivity compared to the HOA specimen without metal powder.

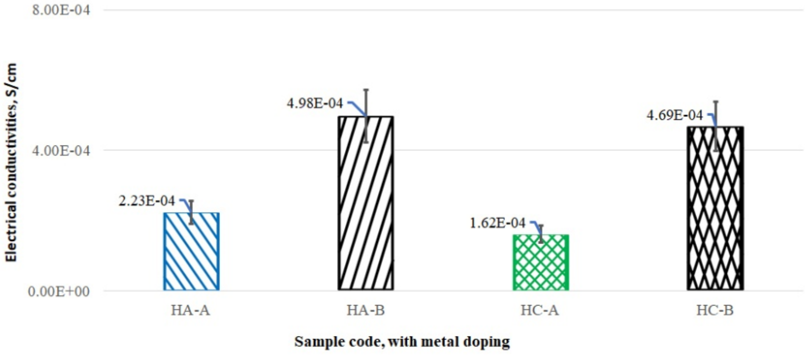

Figure 2. Electrical conductivity of hybrid composite

The distribution of metal fillers in HAA and HCA did not form sufficient conductive channels. The HOA specimen with microcarbon filler mesh #200 (±74 µm) achieved 9.43E-04 S/cm, while HAA (LLDPE/C-Al 10%) and HAB (LDPE/C-Al 20%) achieved 0.000223 S/cm and 0.000498S/cm, respectively, as showed at Table 5.

Table 5. Composition ratio LLDPE-carbon-Al

Sample code	HAA	HAB
LLDPE, %w	50	50
Carbon, %w	40	30

Al powder, %w	10	20
Electrical Conductivities, S/cm	2.23E-04	4.98E-04

A 20% by-weight substitution of micro carbon in hybrid composites increases electrical conductivity, as seen in HAB and HCB specimens, as shown in Figure 2, and Table 5 and 6. However, adding too much metal powder to the LDPE/C carbon polymer composite can decrease conductivity, likely due to metal powder agglomeration within the polymer matrix. Compare the data in Figures 1 and 2, specifically between the HOA (no doping metal), HAA (Al doping metal), and HCA (Cu doping metal) samples.

Table 6. Composition ratio LLDPE-carbon-Cu

Sample code	HCA	HCB
LLDPE, %w	50	50
Carbon, %w	40	30
Cu powder, %w	10	20
Electrical Conductivities, S/cm	1.62E-04	4.69E-04

Adding metal powder Al and Cu to the LLDPE/C carbon polymer composite affects its flow behavior. Metal powders have higher densities than carbon and LLDPE, increasing melt viscosity and reducing the flowability or rheology of LLDPE. This high viscosity can lead to particle agglomeration within the polymer matrix. Metal powder particles, along with microcarbon, act as nuclei for forming conductive pathways. If pressure and thermal energy are insufficient, conductive pathways may not increase during compaction and heating.

Uneven dispersion of conductive filler particles disrupts electrical pathways and reduces charge transfer efficiency in the polymer matrix. Metal powder agglomeration decreases contact between metal and carbon powders, lowering conductivity. Additionally, agglomeration can reduce the composite's density, further decreasing conductivity.

Microstructure dispersion of metal filler LLDPE-carbon composite

The explanation of the SEM test results directly points to the feature points that are suspected to be carbon filler or porosity (voids) or cracks, or LLDPE matrix. Porosity or voids are indicated by very dark images, compared to carbon fillers, and cracks are indicated by irregularly elongated groove images, and usually occur at the interface between the matrix and carbon filler.

In Figure 3, SEM images of the HOA specimen (LLDPE/C) show micro carbon particles from rice husk bound by a polymer layer (LLDPE), forming micro carbon channels in the matrix. These closely packed conductive channels facilitate electron transfer, resulting in a conductivity of 9.43E-04 S/m.

In Figure 3, the SEM test results also show that a metal intrusion has been detected. This intrusion is an impurity in the LLDPE-carbon composite. The detected metal was accidentally included in the composite mixture.

In Figure 3, there is a difference in the contrast of appearance between the carbon filler and the LLDPE matrix. The carbon filler looks darker than the plastic matrix in the SEM image.

LLDPE-carbon and metal aluminum composites are shown in Figure 4 with the HAA sample code. Figures 4 and 5 show SEM images comparing the microstructure of HAA (LLDPE/C-Al) and HCA (LLDPE/C-Cu) specimens, each with a 10% by-weight metal powder loading. The comparison reveals that these composites are more porous than the HOA (LLDPE/C) specimen. In the HAA (LLDPE/C-Al; 50/40/10) and HCA (LLDPE/C-Cu; 50/40/10) specimens, adding 10% metal powder results in relatively good dispersion of metal particles. However, this dispersion does not fully replace the lost conductive microcarbon network. Consequently, the conductivity values of HAA (1.06E-04 S/cm) and HCA (1.33E-04 S/cm) are significantly lower than HOA (9.43E-04 S/cm), which has no metal filler.

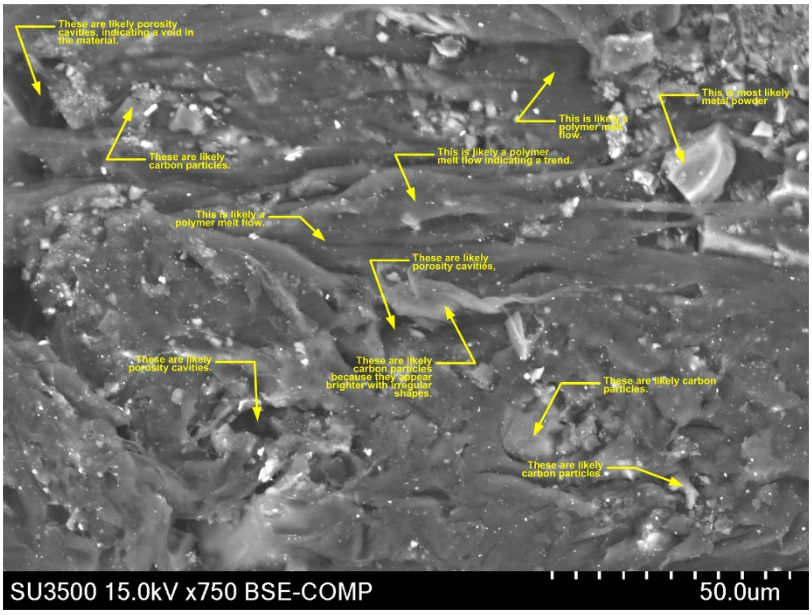

Figure 3. SEM of HOA composite (LLDPE/C)

The composite's conductivity depends on the amount of conductive filler particles, with higher metal content providing a larger surface area per unit volume. This larger surface area improves metal-to-metal contacts and electrical conductivity. With a 20% filler loading, the HAB (1.82E-04 S/cm) and HCB (3.54E-04 S/cm) specimens show the highest conductivity values among the tested compositions. The HCB's conductivity is approximately one-third of the HOA's (9.43E-04 S/cm). These results support the hypothesis that a larger surface area-to-volume ratio of the filler influences conductive channel formation. The HOA specimen has a larger surface area-to-volume ratio for the filler, considering particle size and filler density. In contrast, the HCB specimen, with a 20% copper filler loading, shows higher conductivity than the HCA specimen.

In the LLDPE/C-Al hybrid composite, the aluminum (Al) element shows a decrease in weight percentage at selected points, likely due to poor aggregation with other Al metals or carbon, leading to Al-Polymer-Carbon agglomeration. For the hybrid composite with copper (Cu) filler, the Cu element's weight percentage increases. The decrease in electrical conductivity is suspected to be due to unevenly dispersed conductive aggregates. The overall conductivity value drops significantly due to numerous agglomerated areas with higher resistance.

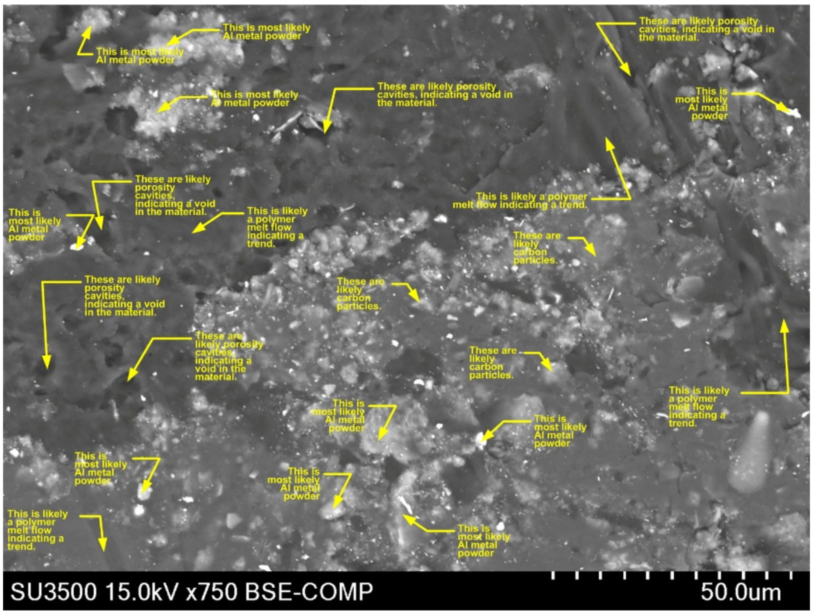

Figure 4. SEM of HAA composite (LLDPE/C-Al)

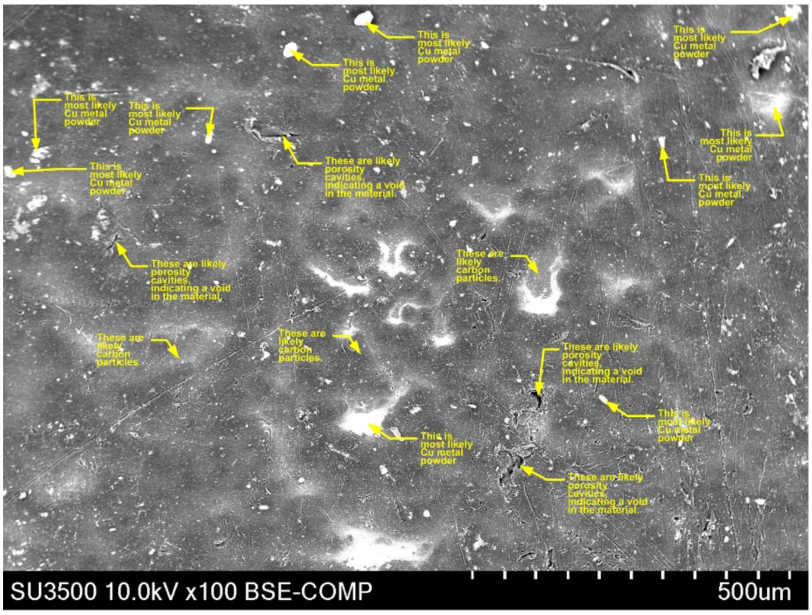

Figure 5. SEM of HCA composite (LLDPE/C-Cu)

SEM analysis of LLDPE/C-Al and LLDPE/C-Cu specimens indicates the occurrence of oxidation on the metal particles within the composite, leading to material degradation on the metal surfaces and resulting in increased contact resistance between metal fillers or between metal fillers and carbon. In carbon polymer composites, metal particles are dispersed throughout the carbon matrix. Exposure to oxygen and other reactive elements leads to oxidation, forming metal oxides like CuO on copper and Al2O3 on aluminum. Oxidation causes metals to lose electrical conductivity, as metal atoms lose electrons and become ions. Metal oxides on particle surfaces decrease conductivity by impeding electron movement and increasing surface roughness, affecting interfacial properties. Copper is more reactive with oxygen than aluminum, making it more prone to oxidation.

In applications where the electrical conductivity of carbon polymer composites is important, steps need to be taken to prevent or minimize the effects of oxidation on the metal particles, such as using antioxidants in the carbon-metal composite mixture [22] or storing the specimens under vacuum conditions [14] to minimize oxygen exposure.

Another factor that contributes to the decrease in electrical conductivity in composites is the high concentration of metal fillers. It becomes more difficult for the metal fillers to disperse effectively in the composite.

A study by Nurazreena et al. (2006) found that Metal-Filled HDPE Composites with 30% aluminum filler had lower electrical conductivity than those with 10%. Conductivity is influenced by the amount and dispersion of conductive fillers and their shape. Regular-shaped fillers tend to agglomerate, reducing adhesion between the metal filler and polymer. Irregular-shaped fillers, like flakes, provide better conductivity due to a larger interfacial contact area [32].

The significant decrease in electrical conductivity in LDPE/C-Al (HAC) and LDPE/C-Cu (HCC) composites with 20% to 30% metal filler loading indicates inverse percolation. This occurs when the conductive filler is not well dispersed or when non-conductive regions hinder conductive pathways, resulting in disrupted pathways and decreased conductivity. Inverse percolation often happens in composites where the filler agglomerates or is poorly dispersed, or when there is a significant mismatch in electrical properties between the filler and the polymer matrix. Further research is needed to determine the specific point of this phenomenon.

4. Conclusion

Adding metal powder generally increases electrical conductivity in carbon polymer composites by filling voids during formation. At low concentrations (≤10%), metal fillers disperse well, forming conductive channels. However, beyond 10% concentration, non-uniform dispersion and agglomeration occur, forming high-concentration aggregates that affect mechanical and electrical properties. Copper particles tend to agglomerate more than aluminum due to higher surface energy and reactivity, forming stronger bonds and aggregates. Additionally, copper's tendency to oxidize in air further contributes to agglomeration.

Funding: The research was funded through the Basic Research Scheme 2024. Contract number: Nomor: 368/PL3.A.10/PT.00.06/2024, April 25, 2024, Politeknik Negeri Jakarta.

Acknowledgments: The authors acknowledge the facilities, scientific and technical support from Advanced Characterization Laboratories, National Research and Innovation Agency through E-Layanan Sains, Badan Riset dan Inovasi Nasional (BRIN), Serpong, Indonesia.

Conflicts of Interest: "The authors declare no conflict of interest."

References

1. Burmistrov, I. *et al.* Improvement of carbon black based polymer composite electrical conductivity with additions of MWCNT. *Compos. Sci. Technol.* **129**, 79–85 (2016).
2. Oberoi, S., Mohan, V. B. & Bhattacharyya, D. Mechanical and Electrical Characteristics of 3D Printed Multi-material Polymer Composites. in *SAMPE Conference Proceeding* (2019).
3. Balberg, I. A comprehensive picture of the electrical phenomena in carbon black-polymer composites. *Carbon N. Y.* **40**, 139–143 (2002).
4. Chiarini, A. & Nitzschner, M. Disconnection and Entropic Repulsion for the Harmonic Crystal with Random Conductances. *Commun. Math. Phys.* **386**, 1685–1745 (2021).
5. Qahtani, N. Al, Ejji, M. Al, Ouederni, M., Almaadeed, M. A. & Madi, N. Effect Of Carbon Black Loading On Linear Low-Density Polyethylene Properties. *Int. J. Sci. Eng. Investig.* **10**, 1–22 (2021).
6. Abdelbary, A. Swelling and electrical properties of LLDPE reinforced by SWCNTs nanocomposites for radiation and sensors applications. *J. Thermoplast. Compos. Mater.* **35**, (2020).
7. Banerjee, J. & Dutta, K. Melt-mixed carbon nanotubes/polymer nanocomposites. *Polym. Compos.* **40**, 4473–4488 (2019).
8. Horst, D. J., Andrade, P. P. J., Duvoisin, C. A. & Vieira, R. D. A. Fabrication of Conductive Filaments for 3D-printing: Polymer Nanocomposites. *Biointerface Res. Appl. Chem.* **10**, 6577–6586 (2020).
9. Choi, H., Kim, M. S., Ahn, D., Yeo, S. Y. & Lee, S. Electrical percolation threshold of carbon black in a polymer matrix and its application to antistatic fibre. *Sci. Rep.* 1–12 (2019) doi:10.1038/s41598-019-42495-1.
10. Kwok, S. W. *et al.* Electrically conductive filament for 3D-printed circuits and sensors. *Appl. Mater. Today* **9**, 167–175 (2017).
11. Leigh, S. J., Bradley, R. J., Purssell, C. P., Billson, D. R. & Hutchins, D. A. A Simple , Low-Cost Conductive Composite Material for 3D Printing of Electronic Sensors. *PLoS One* **7**, 1–6 (2012).
12. Ojha, S., Acharya, S. K. & Raghavendra, G. Mechanical properties of natural carbon black reinforced polymer composites. *J. Appl. Polym. Sci.* **132**, 1–7 (2015).
13. Mamunya, Y. P., Davydenko, V. V., Pissis, P. & Lebedev, E. V. Electrical and thermal conductivity of polymers filled with metal powders. *Eur. Polym. J.* **38**, 1887–1897 (2002).
14. Nurazreena, Hussain, L. B., Ismail, H. & Mariatti, M. Metal filled high density polyethylene composites - Electrical and tensile properties. *J. Thermoplast. Compos. Mater.* **19**, 413–425 (2006).
15. Zare, Y., Rhee, K. Y. & Park, S. J. Advancement of the Power-Law Model and Its Percolation Exponent for the Electrical Conductivity of a Graphene-Containing System as a Component in the Biosensing of Breast Cancer. *Polymers (Basel).* **14**, (2022).
16. Indayaningsih, N., Zulfia, A., Priadi, D. & ... Synthesis of Empty Fruit Bunches Carbon Polymer Composites As Gas Diffusion Layer for Electrode materials. *J. Sains Mater. ...* (2018).

17. Lovelila, B. *et al.* The Study of The Electrical Conductivity and Activation Energy on Conductive Polymer Materials. *Comput. Exp. Res. Mater. Renew. Energy* **4**, 71–79 (2021).
18. Nurdiati, D. & Astuti. Sintesis Komposit PAni / Karbon dari Tempurung Kemiri (Aleurites moluccana) Sebagai Elektroda Kapasitor. *J. Fis. Unand* **4**, 51–57 (2015).
19. Kumar, N., Jain, P. K., Tandon, P. & Pandey, P. M. Investigations on the melt flow behaviour of aluminium filled ABS polymer composite for the extrusion-based additive manufacturing process. *Int. J. Mater. Prod. Technol.* **59**, 194–211 (2019).
20. Anis, A. *et al.* Aluminum-filled amorphous-PET, a composite showing simultaneous increase in modulus and impact resistance. *Polymers (Basel).* **12**, (2020).
21. Boudenne, A., Ibos, L., Fois, M., Majesté, J. C. & Géhin, E. Electrical and thermal behavior of polypropylene filled with copper particles. *Compos. Part A Appl. Sci. Manuf.* **36**, 1545–1554 (2005).
22. Zulfia, A., Abimanyu, T. & Dalam, V. Effect of Copper Addition on Mechanical Properties and Electrical Conductivity of PP/C-Cu Bipolar Plate Composites. *Makara J. Technol.* **15**, 101 (2013).
23. Ramkumar, P. L., Kulkarni, D. M. & Chaudhari, V. V. Parametric and mechanical characterization of linear low density polyethylene (LLDPE) using rotational moulding. *S¯adhan¯a* **39**, 625–635 (2014).
24. Jin-hua, T., Guo-qin, L., Huang, C. & Lin-jian, S. Mechanical Properties and Thermal Behaviour of LLDPE/MWNTs Nanocomposites. *Mater. Res.* **15**, 1050–1056 (2012).
25. Saleem, Anjum; Frormann, Lars; Iqbal, A. High Performance Thermoplastic Composites: Study on the Mechanical, Thermal, and Electrical Resistivity Properties of Carbon Fiber-Reinforced Polyetheretherketone and Polyethersulphone. *Polym. Compos.* **28**, 785–796 (2007).
26. Islam, A., Hansen, H. N. & Tang, P. T. Direct electroplating of plastic for advanced electrical applications. *CIRP Ann. - Manuf. Technol.* **66**, 209–212 (2017).
27. Zuhri, A., Pramono, A. E., Setyadi, I. & Indayaningsih, N. Effect of Rheological on the Physical and Electrical Properties of Extruded Micro Carbon-LLDPE Composites. **02**, (2024).
28. Pramono, A. E. *et al.* The investigation on the electrical and physical properties of conductive filaments prepared using polymer-carbon composites. *AIP Conf. Proc.* **3222**, (2024).
29. Pramono, A. E. *et al.* Jurnal Polimesin. *Polimesin* **22**, 410–415 (2024).
30. Zuhri, A., Pramono, A. E., Setyadi, I., Maksum, A. & Indayaningsih, N. Effect of microcarbon particle size and dispersion on the electrical conductivity of LLDPE-carbon composite. *J. Appl. Res. Technol.* **13**, 374–381 (2024).
31. Pramono, A. & Zulfia, A. Konduktifitas Listrik Komposit Polimer Polipropilena/Karbon Untuk Aplikasi Pelat Bipolar Fuel Cell. *Setrum Sist. Kendali-Tenaga-elektronika-telekomunikasi-komputer* **1**, 46 (2012).
32. Nurazreena, Hussain, L. B., Ismail, H. & Mariatti, M. Metal filled high density polyethylene composites - Electrical and tensile properties. *J. Thermoplast. Compos. Mater.* **19**, 413–425 (2006).