ORIGINAL RESEARCH PAPER

Engineering

PREPARATION AND CHARACTERISATION OF SILICON DIOXIDE/PCB POWDER COMPOSITES FOR ELECTRICAL CONDUCTIVITY APPLICATIONS.

KEY WORDS: E-waste recycling, lithium-ion batteries, printed circuit boards, mechanical alloying, nano-silicon anodes, boron nitride composites, sustainability

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ABSTRACT

The rapid expansion of the electronics industry has led to an unprecedented increase in electronic waste (e-waste),creating significant environmental and economic challenges. Effective recycling methods are necessary to recover valuable materials, reduce pollution, and minimize resource depletion. This paper explores state-of-the-art strategies for the recycling of printed circuit boards (PCBs) and lithium-ion batteries (LIBs), including mechanical alloying, high-purity silica extraction, and the use of boron nitride composites in flexible PCBs. Additionally, advancements in LIB technologies, such as drop-on-demand 3D printing of silicon anodes, nano-silicon electrodes, and the mitigation of performance degradation due to volume expansion, are analyzed. The findings emphasize the importance of developing sustainable, scalable, and economically viable recycling processes to support a circular economy.

1. INTRODUCTION

E-waste has emerged as a pressing global issue due to the rapid consumption of electronic products. The United Nations Global E-waste Monitor reports that over 53.6 million metric tons of e-waste were generated worldwide in 2019, with an expected annual growth rate of 2 million metric tons. The improper disposal of e-waste leads to environmental pollution due to the presence of toxic metals such as lead, mercury, and cadmium. At the same time, it results in the loss of valuable materials, including copper, silver, gold, and rare earth elements. The increasing volume of discarded lithium-ion batteries (LIBs) further complicates this challenge. LIBs are widely used in electronic devices, electric vehicles, and energy storage systems due to their high energy density and long cycle life. However, they contain hazardous materials such as lithium, cobalt, and nickel, which pose environmental and safety risks if not properly managed. Given the finite availability of these raw materials and the rising demand for renewable energy, it is essential to develop efficient recycling strategies. This review provides a comprehensive analysis of innovative recycling techniques for PCBs and LIBs. It explores the potential of mechanical alloying, high-purity silica extraction, and boron nitride composite integration in flexible PCBs. Additionally, it discusses advancements in lithium-ion battery technologies, including the development of 3D-printed silicon anodes, nano-silicon powders, and electrolyte modifications to improve battery performance.

2. Recycling of Printed Circuit Boards (PCBs)

2.1 Mechanical Alloying for Metal Recovery

Mechanical alloying is an emerging solid-state recycling technique that directly converts PCB waste into a homogenous nano-structured metallic alloy. Traditional PCB recycling methods involve pyrometallurgical and hydrometallurgical processes, which require high energy consumption and produce toxic by products. In contrast, mechanical alloying eliminates the need for chemical treatments, significantly reducing environmental impact. This process involves high-energy ball milling, where PCB components are repeatedly fractured and cold-welded, resulting in a fine-grained metal alloy (Cu-Zn-Fe-Sn-Ni). Studies have shown that mechanically alloyed powders exhibit excellent mechanical properties and electrical conductivity, making them suitable for industrial applications such as conductive inks, coatings, and thermal management materials.

2.2 High-Purity Silica Extraction from PCBs

In addition to metallic components, PCBs contain a substantial amount of non-metallic materials such as fiberglass and epoxy resin. Recent research has demonstrated that these non-metallic components can be converted into high-purity porous silica through acid and thermal treatments. This process offers a sustainable approach to waste valorization, providing an alternative to conventional silica production methods, which rely on energy-intensive mining operations. Applications of PCB-derived silica include its use in catalysis, filtration media, and composite materials. The integration of recycled silica in high-performance polymers and coatings further enhances its commercial viability.

2.3 Boron Nitride Composite for Flexible PCBs

Flexible PCBs have gained significant attention in recent years due to their potential applications in wearable electronics and foldable devices. The incorporation of boron nitride nanosheets (BNNs) in flexible PCBs enhances their thermal conductivity and mechanical flexibility. BN-based composites provide effective heat dissipation, which is crucial for high-frequency electronics and power-intensive applications. Recent studies indicate that BN-enhanced flexible PCBs exhibit improved dielectric properties and durability, making them ideal for next-generation electronic circuits. Future research should focus on optimizing the scalability and cost-effectiveness of BN composite fabrication to promote widespread adoption.

3. Advancements in Lithium-Ion Battery (LIB) Technologies

3.1 Drop-on-Demand 3D Printing of Silicon Anodes

Drop-on-demand (DoD) 3D printing has emerged as a promising method for fabricating high-performance lithium-ion battery anodes. Conventional silicon anodes suffer from severe volume expansion during charge-discharge cycles, leading to electrode fracture and capacity degradation. The DoD technique enables the precise deposition of silicon-based materials, improving structural integrity and electrochemical stability. Studies have demonstrated that 3D-printed silicon anodes exhibit higher capacity retention and longer cycle life compared to traditional cast anodes. Additionally, optimized electrode architectures enhance lithium-ion transport kinetics, reducing polarization effects and improving battery efficiency.

3.2 Nano-Silicon Electrodes for High-Energy Batteries

Silicon is a promising anode material for next-generation LIBs due to its high theoretical capacity (4200 mAh/g). However, its practical application is hindered by large volume fluctuations and unstable solid-electrolyte interphase (SEI) formation. To address these challenges, researchers have developed nano-silicon electrodes, which mitigate mechanical stress and enhance electrochemical performance. Nano-silicon anodes with core-shell structures, porous architectures, and graphene-based composites exhibit improved cycle stability and rate capability. Further advancements in binder chemistry and electrolyte formulations are crucial for optimizing the performance of silicon-based anodes in commercial LIBs.

4. Future Perspectives And Challenges

While significant progress has been made in e-waste recycling and LIB advancements, several challenges remain. Industrial scalability, economic feasibility, and regulatory frameworks must be addressed to facilitate the large-scale adoption of sustainable recycling technologies.

4.1 Industrial Scalability of Recycling Methods

The transition from laboratory-scale research to industrial-scale implementation requires substantial investments in infrastructure and process optimization. Mechanical alloying and high-purity silica extraction processes need to be refined to enhance throughput and cost efficiency.

4.2 Environmental And Economic Impacts

Sustainable recycling processes must balance environmental benefits with economic viability. The development of closed-loop recycling systems, where recovered materials are reintegrated into manufacturing cycles, presents an opportunity for reducing resource dependency and production costs.

4.3 Material Performance Optimization

Future research should focus on enhancing the stability and performance of recycled materials. The integration of AI-driven process optimization and machine learning algorithms can accelerate the discovery of novel material compositions and processing techniques.

5. CONCLUSION

Sustainable e-waste recycling and LIB advancements are essential for mitigating environmental pollution and conserving critical raw materials. The methodologies reviewed in this study highlight the potential of mechanical alloying, high-purity silica extraction, and boron nitride composites in revolutionizing e-waste management. Moreover, advancements in 3D-printed silicon anodes and nano-silicon electrodes pave the way for next-generation energy storage technologies. Continued research and policy support are crucial for fostering a circular economy and achieving global sustainability goals.

6. REFERENCES

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