

RESEARCH ARTICLE

Wear and Surface Characterization of Polylactic Acid Composite Filaments Incorporated With Printed Circuit Board Waste for Fused Deposition Modeling

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ABSTRACT

This study investigated the wear behavior and surface characteristics of polylactide (PLA)-based composite filaments engineered for affinity with Fused Deposition Modeling (FDM) processes. Recycled Electronic Waste-derived Printed Circuit Board (EW-PCB) material is employed as a filler at 1 and 3 wt. % by weight. To augment the ductility of the filaments, flexi PLA F2110 is incorporated as a plasticizer. Surface characterization of the samples is assessed by employing wettability measurement, Surface Roughness (SR) analysis, and Surface Hardness (SH) testing. The results exposed that EW-PCB particles enhanced the SH of the composite filament by approximately 5%–10% compared to the neat filament, while concurrently reducing the surface finish quality by up to 20%. Wettability is assessed using water contact angle measurements, revealing a 10% enhancement in surface wettability upon the incorporation of 3 wt. % EW-PCB filler particles. Tribological testing is conducted in accordance with ASTM G99 standards to evaluate the Specific Wear Rate, Frictional Force, and Coefficient of Friction under diverse normal loads and sliding velocities. Response Surface Methodology (RSM) is utilized to model the effects of plasticizer content and filler concentration on wear behavior. Although plasticizer addition and EW-PCB inclusion improve wear performance under mild conditions, they are insufficient to diminish wear under high-load and velocity regimes. Microscopy is employed to conduct post-test morphological evaluations of worn surfaces in order to assess wear mechanisms.

1 | Introduction

In recent decades, technological advancements and the launching of updated gadgets have increased the disposal rate of EW, or Waste Electric and Electronic Equipment (WEEE), in landfills to cause pollution [1]. Based on the data gathered from 2010 to 2021, it was shown that the annual disposal quantity of WEEE has proliferated from 3.8 million tons (mt) (2010) to 5.6 mt (2021). The key contributors to WEEE disposal are countries in Asia and Europe, as well as a few developed nations [2]. The Information and Communications Technology (ICT) gadgets are principally

generating the carbon emissions and noticeably contributing to creating greenhouse gas (GHG) emissions. Emissions from WEEE or EW surpassed emissions from industries such as mining, manufacturing, and transportation. Furthermore, it was found that the generation rate of emissions by GHG has increased up to 53% between 2014 and 2020 [3]. Kiddee et al. [4, 5] claimed that 53.6 mt of EW were generated globally, with every individual contributing an average of 7.3 kg in 2021. In 2014, the quantity of generated e-waste was approximately 45 mt, and it is anticipated to rise to 74.3 mt by 2030. Robinson [6] developed an Equation (i) to enumerate the annual generation of EW, denoted as (E), by taking into account the

mass of the product (M), the number of products in working order (N), and the expected product life span (L).

$$E = \frac{MN}{L} \quad (i)$$

Globally, China stands as the biggest producer of EW, with India being the second-largest producer [7].

In 2022, the trade value of raw materials in EW was nearly fifty-five billion dollars, and it is forecasted to surge to 240 billion dollars by 2032 [8]. Unpredictably, the global recycling percentage of e-waste is only 15% of its total quantity [9]. The circular economy of the plastics from the EW is not akin to the plastics accumulated from other sources. It is challenging to recycle the plastics gathered from EW because they contain thermoset plastic material [10]. The PCB is a crucial part of EW and contains valuable metals like aluminum (Al), gold (Au), silver (Ag), copper (Cu), zinc (Zn), and more [11]. Waste management is a fairly new notion in nations that are evolving. There is widespread agreement that addressing the disposal of diverse plastic wastes in workshops is critical. Establishing recycling goals for certain types of plastic trash is an important step toward improving the nation's plastic waste disposal system [12]. The circular economy of e-waste, or WEEE, is incredibly limited due to the high inherent sophistication processes required for collecting and recycling [13].

A major concern in the reuse of WEEE is detaching the PCB from the other associated materials. Indeed, EW-PCBs consist of variable quantities of materials like Cu, Zn, Au, and Ag that are merged together [14]. Detaching the PCB materials from the WEEE is imperative to accomplish reuse procedures. Because PCBs contain many hazardous parts, they may contaminate the soil [15]. The contaminant particles detected from PCBs are arsenic, cadmium, lead, mercury, and many more hazardous materials [15]. Currently, in undeveloped nations, the methods for detaching the metals from EW involve ancient techniques like chipping and burning on the open surface without proper safety measures. This practice leads to pollution of the environment and affects human health [16]. Many approaches and research are advancing to diminish the formation of GHGs generated by ICT equipment [17].

Thus, a sleek procedure is mandatory for recycling the PCB of ICT equipment. Recent studies have utilized additive manufacturing techniques to recycle the used and failed parts of polymer materials as an eco-friendly approach [18]. Because this process can make an optimized model of complex design parts with a minimal quantity of materials [19]. Few researchers have demonstrated the possibility of integrating the plastic wastes with virgin materials for 3D printing and highlighted it as a sustainable method. Similar to commercial filament, the parts developed from recycled plastics showed the best results by selecting the suitable process parameters of FDM processes [20]. The materials sorted from WEEE for recycling were properly valorized by being transformed into a filament for FDM processes. The life cycle assessment (LCA) investigation recommended that the plastics be extracted from WEEE as a source material rather than virgin polymers. It led to a reduction of CO₂ emissions by up to 30% [21]. Spirio et al. [22] utilized the FDM technique to reuse the polypropylene (PP) gathered from the WEEE. The sorted PP from WEEE was ground into small particles and blended with virgin material to modify it into a filament

for FDM processes. Likewise, the main outcome of this research is to recycle the amassed PCB derived from EW. The objective is achieved through integrating with PLA material aligned with the net zero concept. The main emphasis of net zero is to motivate the usage of renewable sources for diminishing GHG [23].

This study concentrates on reusing the PCB of EW or WEEE in 3D printing as an approach for diminishing the formation of GHG. Hence, PCBs from ICT equipment were ground as fine particles (150 μm) and recycled with virgin PLA as a filament for 3D printing [24]. Virgin PLA is a pure material manufactured without involving recycled polymeric elements. Obviously, PLA is a brittle material, and plasticizers have to be involved to enhance the ductility [25, 26]. Flexi PLA F2110 is opted as a plasticizer to elevate its properties for 3D printing [26]. The traditional blending method was followed for incorporating the fillers with virgin PLA. In the traditional method, ball milling is employed for combining virgin PLA pellets, EW filler particles (1 and 3 wt. %), and flexi PLA F2110 to extrude as a filament. Mechanical characterization tests (tensile, flexural, compression, and impact tests) were conducted to assess the impact of integrating EW-PCB as a filler and Flexi PLA F2110 as a plasticizer. The results demonstrated that this combination improved both impact and compression strength, as well as enhanced surface hardness [27, 28]. In this current study, a detailed study about the influence of filler and plasticizer on surface characteristics is investigated. The study focuses on evaluating the wettability behavior and sliding resistance of the fabricated composite filaments to identify their appropriateness for potential application-specific functionalities. The surface properties of the developed composites are investigated by performing water droplet tests and surface hardness and roughness tests [29, 30]. Furthermore, sliding resistance was assessed through wear testing using a pin-on-disc tribometer. As per the ASTM G99 standard, the cylindrical samples are printed with a diameter of 10 mm and a height of 30 mm and were prepared to examine the wear behavior of the composite filaments under dry sliding conditions [31]. The study primarily focuses on evaluating the influence of plasticizer additives and filler particulates on the tribological response and surface characteristics of the material.

In this study, a RSM technique is utilized for analyzing the influence of three key parameters such as applied load, applied velocity, and filler composition on the coefficient of friction, specific wear rate, and friction force. These control factors are considered as independent input variables, and their individual as well as interactive effects on the tribological responses were investigated through RSM-generated surface plots [32–34]. The surface morphology of the evaluated specimens was characterized using Scanning Electron Microscopy (SEM) to investigate the material's wear mechanisms under sliding contact conditions.

2 | Filament Extrusion and Testing Methods

2.1 | Composite Filament Extrusion

The acquired EW-PCB underwent initial analysis to classify and remove hazardous constituents. Following standard safety protocols, toxic components were manually separated. Then the accumulated PCB from EW was shredded by employing the shredding machine with a size of 400–600 μm. Then the shredded particles

4 | Conclusion

The influence of the plasticizer (flexi PLA F2110) and filler (EW-PCB) on the surface characteristics and wear behavior of the composite filament was thoroughly investigated, and the outcomes are presented. The incorporation of plasticizer significantly condensed the inherent brittleness of virgin PLA, enhancing the ductility and overall flexibility of the polymer matrix. However, the addition of the plasticizer and filler particles resulted in a diminution of about 20% in the density of the 3D-printed specimens. This diminution is predominantly due to the formation of voids within the printed structure, emerging from material conflict and the thermal volatility of the plasticizer at elevated processing temperatures, which collectively lead to deficient interfacial bonding and increased porosity. The presence of the metallic constituents within the filler particles leads to an increment in surface roughness, elevating the roughness values by up to 20% compared to the plain PLA filament without EW-PCB incorporation. Conversely, the incorporation of filler particles enhanced both surface hydrophobicity and hardness, resulting in enhanced resistance to wettability and applied load on the surface by approximately 10%–15% relative to the neat PLA filament. These enhancements exhibit that the fabricated composite filament is of potential suitability for fabricating prosthetic models in medical applications.

The wear behavior of the composite was comprehensively evaluated under a range of applied normal loads and sliding velocities. The findings indicate that flexi PLA F2110 exhibits insufficient thermal stability under higher mechanical and thermal stress conditions—specifically at loading levels (20 and 30 N) and sliding velocities (2 and 3 m/s). This thermal limitation impairs the

interfacial adhesion between the polymer matrix and the filler particles, thereby accelerating the wear rate of the composite material. Furthermore, response surface methodology (RSM) plots are employed to methodically evaluate the influence of crucial process factors on the wear performance of composite materials. The factors to consider included filler concentration, applied load, and sliding velocity. The RSM analysis revealed that the combination of elevated filler content and enhanced mechanical loading, particularly at high sliding velocities, considerably enhanced the wear rate of the 3D-printed samples.

In further studies, void formation within the printed samples can be controlled by integrating a plasticizer that has greater thermal stability. This modification may lead to diminishing the aggregate wear rate. Additionally, by involving post-processing methods like chemical vapor dip and immersion techniques using solvents like dichloromethane, acetone, and ethyl acetate to enhance the surface finish of the specimens, it may enhance wear resistance in high-load and high-velocity conditions, minimizing the aggregate wear rate.

Author Contributions

Yogeshwaran Kumarasamy: writing – original draft, methodology, formal analysis. **Prases Kumar Mohanty:** writing – review and editing, methodology, supervision. **Nagarjun Jayakumar:** conceptualization. **Shubhajit Das:** supervision.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

References

1. J. Cui and E. Forssberg, “Mechanical Recycling of Waste Electric and Electronic Equipment: A Review,” *Journal of Hazardous Materials* 99, no. 3 (2003): 243–263, [https://doi.org/10.1016/s0304-3894\(03\)00061-x](https://doi.org/10.1016/s0304-3894(03)00061-x).
2. C. P. Balde Baldé, G. Iattoni, C. Xu, and T. Yamamoto, “United Nations Institute for Training and Research (UNITAR) Sustainable Cycles (SCYCLE) Programme,” Update of WEEE Collection Rates, Targets, Flows, and Hoarding – 2021 in the EU-27, United Kingdom, Norway, Switzerland, and Iceland, United Nations Institute for Training and Research (UNITAR), 2022, https://weee-forum.org/wp-content/uploads/2022/12/Update-of-WEEE-Collection_web_final_nov_29.pdf.
3. N. Singh and O. A. Ogunseitan, “Disentangling the Worldwide Web of e-Waste and Climate Change Co-Benefits,” *Circular Economy* 1, no. 2 (2022): 100011, <https://doi.org/10.1016/j.ccc.2022.100011>.
4. P. Kiddee, R. Naidu, M. H. Wong, L. Hearn, and J. F. Muller, “Field Investigation of the Quality of Fresh and Aged Leachates From Selected Landfills Receiving e-Waste in an Arid Climate,” *Waste Management* 34, no. 11 (2014): 2292–2304, <https://doi.org/10.1016/j.wasman.2014.06.018>.
5. P. Kiddee, J. K. Pradhan, S. Mandal, et al., *An Overview of Treatment Technologies of E-Waste* (Elsevier eBooks, 2019), 1–18, <https://doi.org/10.1016/b978-0-12-817030-4.00022-x>.
6. B. H. Robinson, “E-Waste: An Assessment of Global Production and Environmental Impacts,” *Science of the Total Environment* 408, no. 2 (2009): 183–191, <https://doi.org/10.1016/j.scitotenv.2009.09.044>.

7. V. Forti, C. P. Baldé, R. Kuehr, et al., "The Global E-Waste Monitor 2020: Quantities, Flows and the Circular Economy Potential," 2020 United Nations University (UNU), https://ewastemonitor.info/wp-content/uploads/2020/11/GEM_2020_def_july1_low.pdf.
8. Allied Market Research, "E-Waste Management Market Size, Share, Competitive Landscape and Trend Analysis Report, by Material, by Source Type, by Application: Global Opportunity Analysis and Industry Forecast, 2022–2032," <https://www.alliedmarketresearch.com/e-waste-management-market>.
9. M. Heacock, C. B. Kelly, K. A. Asante, et al., "E-Waste and Harm to Vulnerable Populations: A Growing Global Problem," *Environmental Health Perspectives* 124, no. 5 (2015): 550–555, <https://doi.org/10.1289/ehp.1509699>.
10. P. Hennebert and M. Filella, "WEEE Plastic Sorting for Bromine Essential to Enforce EU Regulation," *Waste Management* 71 (2017): 390–399, <https://doi.org/10.1016/j.wasman.2017.09.031>.
11. P. Pokhrel, S. L. Lin, and C. T. Tsai, "Environmental and Economic Performance Analysis of Recycling Waste Printed Circuit Boards Using Life Cycle Assessment," *Journal of Environmental Management* 276 (2020): 111276, <https://doi.org/10.1016/j.jenvman.2020.111276>.
12. R. Weber, C. Gaus, M. Tysklind, et al., "Dioxin- and POP-Contaminated Sites—Contemporary and Future Relevance and Challenges," *Environmental Science and Pollution Research* 15, no. 5 (2008): 363–393, <https://doi.org/10.1007/s11356-008-0024-1>.
13. J. A. P. Silva, G. G. Lima, C. F. Camilo-Cotrim, et al., "Impact of E-Waste Toxicity on Health and Nature: Trends, Biases, and Future Directions," *Water, Air, and Soil Pollution* 234, no. 5 (2023): 320, <https://doi.org/10.1007/s11270-023-06328-2>.
14. G. Martinho, A. Pires, L. Saraiva, and R. Ribeiro, "Composition of Plastics From Waste Electrical and Electronic Equipment (WEEE) by Direct Sampling," *Waste Management* 32, no. 6 (2012): 1213–1217, <https://doi.org/10.1016/j.wasman.2012.02.010>.
15. J. Maris, S. Bourdon, J. M. Brossard, L. Cauret, L. Fontaine, and V. Montebault, "Mechanical Recycling: Compatibilization of Mixed Thermoplastic Wastes," *Polymer Degradation and Stability* 147 (2017): 245–266, <https://doi.org/10.1016/j.polymdegradstab.2017.11.001>.
16. M. H. Wong, S. C. Wu, W. J. Deng, et al., "Export of Toxic Chemicals – A Review of the Case of Uncontrolled Electronic-Waste Recycling," *Environmental Pollution* 149, no. 2 (2007): 131–140, <https://doi.org/10.1016/j.envpol.2007.01.044>.
17. L. Belkhir and A. Elmeligi, "Assessing ICT Global Emissions Footprint: Trends to 2040 & Recommendations," *Journal of Cleaner Production* 177 (2018): 448–463, <https://doi.org/10.1016/j.jclepro.2017.12.239>.
18. A. Lanzotti, M. Martorelli, S. Maietta, S. Gerbino, F. Penta, and A. Gloria, "A Comparison Between Mechanical Properties of Specimens 3D Printed With Virgin and Recycled PLA," *Procedia CIRP* 79 (2019): 143–146, <https://doi.org/10.1016/j.procir.2019.02.030>.
19. E. Sanchez-Rexach, T. G. Johnston, C. Jehanno, H. Sardon, and A. Nelson, "Sustainable Materials and Chemical Processes for Additive Manufacturing," *Chemistry of Materials* 32, no. 17 (2020): 7105–7119, <https://doi.org/10.1021/acs.chemmater.0c02008>.
20. J. Kechagias and D. Chaidas, "Fused Filament Fabrication Parameter Adjustments for Sustainable 3D Printing," *Materials and Manufacturing Processes* 38, no. 8 (2023): 933–940, <https://doi.org/10.1080/10426914.2023.2176872>.
21. V. Gaikwad, A. Ghose, S. Cholake, A. Rawal, M. Iwato, and V. Sahajwalla, "Transformation of E-Waste Plastics Into Sustainable Filaments for 3D Printing," *ACS Sustainable Chemistry & Engineering* 6, no. 11 (2018): 14432–14440, <https://doi.org/10.1021/acssuschemeng.8b03105>.
22. A. Spirio, R. Arrigo, A. Frache, L. Tuccinardi, and R. Tuffi, "Plastic Waste Recycling in Additive Manufacturing: Recovery of Polypropylene From WEEE for the Production of 3D Printing Filaments," *Journal of Environmental Chemical Engineering* 12, no. 3 (2024): 112474, <https://doi.org/10.1016/j.jece.2024.112474>.
23. B. I. Oladapo, O. K. Bowoto, V. A. Adebisi, and O. M. Ikumapayi, "Net Zero on 3D Printing Filament Recycling: A Sustainable Analysis," *Science of the Total Environment* 894 (2023): 165046, <https://doi.org/10.1016/j.scitotenv.2023.165046>.
24. V. Linares, E. Galdón, M. Casas, and I. Caraballo, "Critical Points for Predicting 3D Printable Filaments Behaviour," *Journal of Drug Delivery Science and Technology* 66 (2021): 102933, <https://doi.org/10.1016/j.jddst.2021.102933>.
25. W. Zhong, F. Li, Z. Zhang, L. Song, and Z. Li, "Short Fiber Reinforced Composites for Fused Deposition Modeling," *Materials Science and Engineering A* 301, no. 2 (2001): 125–130, [https://doi.org/10.1016/S0921-5093\(00\)01810-4](https://doi.org/10.1016/S0921-5093(00)01810-4).
26. D. Rahmatabadi, I. Ghasemi, M. Baniassadi, K. Abrinia, and M. Baghani, "3D Printing of PLA-TPU With Different Component Ratios: Fracture Toughness, Mechanical Properties, and Morphology," *Journal of Materials Research and Technology* 21 (2022): 3970–3981, <https://doi.org/10.1016/j.jmrt.2022.11.024>.
27. Y. Kumarasamy, N. Jayakumar, P. K. Mohanty, and S. Das, "Transforming Electronic Waste Into a Sustainable 3D Printing Filaments Using Polylactic Acid," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 239 (2024): 2424–2441, <https://doi.org/10.1177/09544062241301594>.
28. Y. Kumarasamy, P. K. Mohanty, N. Jayakumar, and S. Das, "Enhancing 3D Printing With Composite Filaments Incorporating Electronic Waste: A Study on Flexural and Compression Strength," *International Polymer Processing* 40 (2025): 178–190, <https://doi.org/10.1515/ipp-2024-0090>.
29. M. M. Zerankeshi, S. S. Sayedain, M. Tavangarifard, and R. Alizadeh, "Developing a Novel Technique for the Fabrication of PLA-Graphite Composite Filaments Using FDM 3D Printing Process," *Ceramics International* 48, no. 21 (2022): 31850–31858, <https://doi.org/10.1016/j.ceramint.2022.07.117>.
30. S. K. Prajapati and R. Gnanamoorthy, "Effect of the Infill Percentage of 3D Printed Polyetheretherketone Under the Dry Sliding Condition," *Journal of Manufacturing Processes* 131 (2024): 2073–2081, <https://doi.org/10.1016/j.jmapro.2024.10.035>.
31. Ş. Şirin, E. Aslan, and G. Akincioglu, "Effects of 3D-Printed PLA Material With Different Filling Densities on Coefficient of Friction Performance," *Rapid Prototyping Journal* 29, no. 1 (2022): 157–165, <https://doi.org/10.1108/rpj-03-2022-0081>.
32. A. Purohit and A. Satapathy, "Development and Characterization of Epoxy-Based Composites Filled With Linz–Donawitz Sludge," *Journal of Composite Materials* 51, no. 7 (2016): 899–911, <https://doi.org/10.1177/0021998316656478>.
33. A. Purohit and A. Satapathy, "Processing, Characterization, and Parametric Analysis of Erosion Behavior of Epoxy-LD Sludge Composites Using T Aguchi Technique and Response Surface Method," *Polymer Composites* 39, no. S4 (2018): E2283–E2297, <https://doi.org/10.1002/pc.24610>.
34. A. Purohit, A. Satapathy, P. T. R. Swain, and P. K. Patnaik, "Analysis of Sliding Wear Behavior of LD Sludge Filled Epoxy Composites Using Response Surface Methodology," *Materials Today Proceedings* 2020, no. 33 (2020): 5066–5069, <https://doi.org/10.1016/j.matpr.2020.02.845>.
35. X. Song, W. He, P. Chen, Q. Wei, J. Wen, and G. Xiao, "Fused Deposition Modeling of Poly (Lactic Acid)/almond Shell Composite Filaments," *Polymer Composites* 42, no. 2 (2020): 899–913, <https://doi.org/10.1002/pc.25874>.
36. J. Nagarjun, J. Kanchana, G. RajeshKumar, S. Manimaran, and M. Krishnaprakash, "Enhancement of Mechanical Behavior of PLA Matrix

- Using Tamarind and Date Seed Micro Fillers,” *Journal of Natural Fibers* 19, no. 12 (2021): 4662–4674, <https://doi.org/10.1080/15440478.2020.1870616>.
37. E. J. Joseph and K. Panneerselvam, “Effect of Particulate Fillers on Mechanical, Metallurgical and Abrasive Behavior of Tungsten Reinforced HDPE Composites: A Taguchi Approach,” *Materials Today: Proceedings* 39 (2020): 1228–1234, <https://doi.org/10.1016/j.matpr.2020.04.042>.
38. M. Salignon, S. Gray, T. Rose, and A. Encinas-Oropesa, “A New Preparation Method for 3D Bio-Composite Filament Manufacturing: A Study on the Effects of Ball Milling on the Cohesion/Adhesion of an *Agave tequilana* Bagasse/PLA Pellet Mixture,” *Circular Economy and Sustainability* 3, no. 3 (2022): 1441–1459, <https://doi.org/10.1007/s43615-022-00241-2>.
39. R. Brown, “Mass, Density, and Dimensions,” in *CRC Press eBooks* (Springer, 2006), 95–108.
40. A. Purohit, P. Pradhan, S. Palanimuthu, A. Kumar, and P. K. Chauhan, “Mechanical and Tribological Characteristics of Glass Fiber and Rice Stubble-Filled Epoxy-LD Sludge Hybrid Composites,” *Journal of Elastomers and Plastics* 57 (2024): 113–131, <https://doi.org/10.1177/00952443241305709>.
41. N. J., “Revalorisation of Tamarind Seed Waste for Improved PLA Wear and Hydrophilic Behaviour in 3D Printing Applications,” *Biomass Conversion and Biorefinery* 14 (2024): 23695–23708, <https://doi.org/10.1007/s13399-023-04531-z>.
42. K. N. Gunasekaran, V. Aravinth, C. B. M. Kumaran, K. Madhan-kumar, and S. P. Kumar, “Investigation of Mechanical Properties of PLA Printed Materials Under Varying Infill Density,” *Materials Today: Proceedings* 45 (2020): 1849–1856, <https://doi.org/10.1016/j.matpr.2020.09.041>.
43. Y. S. Zeng, M. H. Hsueh, C. J. Lai, et al., “An Investigation on the Hardness of Polylactic Acid Parts Fabricated via Fused Deposition Modeling,” *Polymers* 14, no. 14 (2022): 2789, <https://doi.org/10.3390/polym14142789>.
44. T. Kar and A. Goswami, “Fabrication of Superhydrophobic Titanium Surfaces: Impact of Different Micropatterns,” *Materials and Manufacturing Processes* 39, no. 16 (2024): 1–2265, <https://doi.org/10.1080/10426914.2024.2394998>.
45. S. Mohanty, A. K. Das, and A. R. Dixit, “Surface Integrity and Residual Stress Analysis of μ EDM Coated Ti-Alloy Miniature Components,” *Materials and Manufacturing Processes* 36, no. 1 (2020): 48–58, <https://doi.org/10.1080/10426914.2020.1813894>.
46. A. I. Portoacă, R. G. Ripeanu, A. Diniță, and M. Tănase, “Optimization of 3D Printing Parameters for Enhanced Surface Quality and Wear Resistance,” *Polymers* 15, no. 16 (2023): 3419, <https://doi.org/10.3390/polym15163419>.
47. O. A. Mohamed, S. H. Masood, J. L. Bhowmik, and A. E. Somers, “Investigation on the Tribological Behavior and Wear Mechanism of Parts Processed by Fused Deposition Additive Manufacturing Process,” *Journal of Manufacturing Processes* 29 (2017): 149–159, <https://doi.org/10.1016/j.jmapro.2017.07.019>.
48. S. Singh, R. K. Attri, and S. Trivedi, “Optimization of FDM 3D Printing Process Parameters for Improving Wear Characteristics of PLA-nGr Composite Using Taguchi DOE,” *Journal of Materials Engineering and Performance* 34 (2024): 15179–15187, <https://doi.org/10.1007/s11665-024-10170-w>.
49. N. H. Kumar, H. Adarsha, R. Keshavamurthy, and G. L. A. Kumar, “Influence of Carbon Nano Fibres on Friction and Wear Characteristics of Polymer Composites Synthesized by Fused Deposition Modelling,” *Journal of the Institution of Engineers (India): Series D* (2024), <https://doi.org/10.1007/s40033-024-00747-z>.
50. B. Gangil, A. Patnaik, A. Kumar, and M. Kumar, “Investigations on Mechanical and Sliding Wear Behaviour of Short Fibre-Reinforced Vinylester-Based Homogenous and Their Functionally Graded Composites,” *Proceedings of the Institution of Mechanical Engineers Part L Journal of Materials Design and Applications* 226, no. 4 (2012): 300–315, <https://doi.org/10.1177/1464420712450956>.