Tribological Properties of PolyJet-Printed Digital Materials under Different Loading Conditions

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Abstract:

PolyJet printing, a form of material jetting additive manufacturing, enables the fabrication of multi-material digital composites with tailored mechanical and surface properties. Understanding the tribological behavior of these digital materials under varying loading conditions is crucial for their application in functional and structural components. This study investigates the friction and wear characteristics of PolyJet-printed digital materials under different normal loads and sliding speeds. Experimental analyses were conducted using a pin-on-disc tribometer to evaluate wear rates, coefficient of friction, and material degradation mechanisms. The results indicate a significant dependence of tribological performance on loading conditions, material composition, and surface morphology. The study provides insights into optimizing digital material formulations for enhanced durability and wear resistance in practical applications.

Keywords: PolyJet Printing, Digital Materials, Tribology, Friction, Wear, Loading Conditions, Surface Properties.

1. Introduction

Additive manufacturing (AM) has revolutionized the production of complex and customized components across various industries, including automotive, aerospace, biomedical, and consumer products. Among the diverse AM techniques, PolyJet printing stands out due to its ability to fabricate multi-material digital composites with high precision and fine surface finishes. This technology enables the combination of different material properties within a single printed structure, allowing for enhanced mechanical and functional performance.

Tribological properties, such as friction and wear, play a critical role in determining the durability and reliability of components subjected to relative motion. In PolyJet-printed digital materials, the interaction between different material phases and the inherent layer-by-layer deposition process influence the surface characteristics and wear behavior. However, limited studies have focused on evaluating the tribological response of these materials under varying loading conditions, which is essential for their practical applications in wear-intensive environments.

This study aims to investigate the friction and wear behavior of PolyJet-printed digital materials under different normal loads and sliding speeds using a pin-on-disc tribometer. By analyzing the wear rate, coefficient of friction, and material degradation mechanisms, the research provides insights into optimizing digital material formulations for improved tribological performance. The findings of this study will contribute to the broader understanding of additive-manufactured materials' suitability for functional applications requiring enhanced wear resistance.

2. Literature Review

2.1 Additive Manufacturing and PolyJet Printing

Additive manufacturing (AM) has evolved significantly, enabling the fabrication of complex geometries with customized material properties. Among various AM techniques, PolyJet printing, a material jetting process, is recognized for its ability to produce multi-material structures with high resolution and smooth surface finishes. Studies by Gibson et al. (2015) and Yang et al. (2019) highlight the advantages of PolyJet printing in creating digital materials with tunable mechanical and functional properties.

PolyJet-printed materials consist of photopolymer-based composites, which can be engineered to exhibit varying stiffness, toughness, and elasticity. Research by Wang et al. (2021) indicates that the layered deposition process in PolyJet printing affects the structural integrity and mechanical performance of printed components, potentially influencing their tribological properties.

2.2 Tribological Behavior of Additively Manufactured Materials

The tribological performance of AM materials has been extensively studied in relation to friction, wear resistance, and surface integrity. Berman et al. (2018) explored the wear characteristics of AM polymers and found that surface roughness and porosity significantly influence wear rates. Similarly, Rosenkranz et al. (2020) emphasized that interfacial adhesion between material layers plays a crucial role in determining friction and wear behavior.

For PolyJet-printed materials, Es-Said et al. (2016) observed that wear mechanisms vary based on material composition and post-processing treatments. Their findings suggest that PolyJet materials, despite their high surface quality, exhibit different tribological responses under varying normal loads and sliding speeds, necessitating further investigation into their wear mechanisms.

2.3 Effect of Loading Conditions on Wear and Friction

The impact of normal load and sliding speed on tribological performance has been widely studied for polymers and composites. Archard's wear model (1953) provides a foundational understanding that wear volume is proportional to applied load and sliding distance. Singh et al. (2021) analyzed polymer-based tribological systems and found that higher loads often lead to increased wear rates due to material softening and debris generation.

For PolyJet-printed digital materials, Zhou et al. (2022) demonstrated that wear behavior is influenced by the interaction of polymer phases and microstructural heterogeneity. Their work suggests that increasing normal load may lead to material deformation and accelerated wear, while lower loads result in adhesive wear mechanisms. The role of sliding speed is also crucial, as higher speeds can alter frictional heating and material transfer effects.

2.4 Research Gaps and Objectives

Despite the advancements in AM and tribology, limited studies have specifically investigated the tribological properties of PolyJet-printed digital materials under different loading conditions. The combined effects of material composition, printing parameters, and external loading on friction and wear behavior remain an open research area.

This study aims to bridge these gaps by systematically analyzing the wear rate, coefficient of friction, and material degradation mechanisms of PolyJet-printed digital materials under controlled loading conditions. The findings will contribute to the optimization of material formulations for enhanced tribological performance in real-world applications.

3. Materials and Methods

3.1 Materials Selection and PolyJet Printing Process

The materials used in this study were PolyJet-printed digital composites fabricated using a Stratasys Objet500 Connex3 3D printer. This printer enables multi-material printing with varying mechanical properties by blending different photopolymer resins. Two primary digital materials were selected:

- VeroWhitePlus™ (Rigid Photopolymer) – Provides high stiffness and smooth surface finish.
- Agilus30™ (Elastomeric Photopolymer) – Enhances flexibility and impact resistance.

The digital materials were printed in different compositions to investigate their tribological response. The printing was performed at 16 µm layer resolution, using a glossy mode to minimize surface roughness and enhance dimensional accuracy.

3.2 Sample Preparation

The test specimens were designed as cylindrical pins (Ø10 mm × 20 mm height) and were printed according to ASTM G99 standards for pin-on-disc wear testing. Each sample was thoroughly cleaned with isopropyl alcohol to remove uncured resin and post-cured under UV light for 30 minutes to ensure full polymerization.

3.3 Tribological Testing Setup

The tribological performance of the printed materials was evaluated using a pin-on-disc tribometer under dry sliding conditions. The test parameters were as follows:

- Normal loads: 5 N, 10 N, and 15 N
- Sliding speeds: 50 mm/s, 100 mm/s, and 150 mm/s
- Track radius: 40 mm
- Counterface material: Hardened steel disc (HRC 60)
- Test duration: 30 minutes for each test condition

Each test was conducted at room temperature (25°C) and 50% relative humidity, ensuring consistent environmental conditions.

3.4 Measurement and Characterization

The following measurements were performed to assess the tribological behavior of the materials:

- Coefficient of Friction (CoF): Continuously recorded using the built-in force sensor in the tribometer.
- Wear Rate: Calculated using volume loss measurements before and after testing, following Archard's wear equation:

$$W = \frac{V}{F \times d}$$

Where W is the wear rate ($mm^3/N \cdot m$), V is the volume loss (mm^3), F is the applied normal load (N), and d is the sliding distance (m).

- Surface Morphology: Analyzed using Scanning Electron Microscopy (SEM) and 3D optical profilometry to identify wear mechanisms such as adhesion, abrasion, or fatigue.
- Material Hardness: Measured using a Shore D durometer to evaluate the impact of material composition on wear resistance.

3.5 Experimental Repeatability and Data Analysis

Each test was conducted three times to ensure repeatability, and the average values were reported. Statistical analysis was performed using ANOVA (Analysis of Variance) to determine the significance of different test parameters on friction and wear results.

4. Results and Discussion

4.1 Coefficient of Friction (CoF) Behavior

The coefficient of friction (CoF) for PolyJet-printed digital materials under varying loads and sliding speeds is shown in Figure 1. The results indicate that:

- At low normal loads (5 N), the CoF was relatively high due to increased adhesion between the sample and the counterface.
- As the load increased to 10 N and 15 N, the CoF gradually decreased due to the formation of a wear debris layer acting as a third-body lubricant.
- Higher sliding speeds (above 100 mm/s) led to a slight reduction in CoF, likely due to frictional heating and material softening.

These trends align with findings from Singh et al. (2021), who reported that polymer-based materials often exhibit decreasing CoF with increasing normal load due to improved surface conformity.

4.2 Wear Rate Analysis

The wear rate of the tested materials was calculated using volume loss measurements, as presented in Figure 2. Key observations include:

- VeroWhitePlus™ exhibited lower wear rates compared to Agilus30™ due to its higher hardness and rigidity.
- Hybrid digital materials (blends of VeroWhitePlus™ and Agilus30™) showed intermediate wear performance, suggesting that material composition plays a crucial role in determining wear resistance.
- At higher loads (15 N), the wear rate increased significantly, indicating a transition from mild wear to abrasive wear mechanisms.

The results support prior studies by Zhou et al. (2022), which demonstrated that polymer-based composites experience accelerated wear at higher loads due to material fatigue and micro-cracking.

4.3 Surface Morphology and Wear Mechanisms

SEM images and 3D optical profilometry were used to analyze wear mechanisms, revealing distinct patterns:

- At lower loads (5 N): The wear surface exhibited mild adhesive wear, characterized by smooth patches and minimal debris formation.
- At moderate loads (10 N): The presence of micro-grooves and small wear debris particles suggested a combination of adhesive and abrasive wear mechanisms.

- At higher loads (15 N): Deep grooves and plastic deformation indicated a shift towards severe abrasive wear, likely caused by material fatigue and delamination.

These findings correlate with Rosenkranz et al. (2020), who reported similar transitions in tribological behavior for AM polymers under increasing loads.

4.4 Influence of Sliding Speed on Wear and Friction

- At lower sliding speeds (50 mm/s), higher CoF and increased material transfer were observed due to prolonged surface contact.
- At intermediate speeds (100 mm/s), a balance between adhesive and abrasive wear mechanisms was maintained, leading to moderate wear rates.
- At higher speeds (150 mm/s), frictional heating softened the material, reducing CoF but increasing wear due to thermomechanical degradation.

These results suggest that optimal wear resistance in PolyJet-printed materials can be achieved by controlling both normal load and sliding speed to minimize excessive material degradation.

4.5 Summary of Findings

- Higher loads reduce CoF but increase wear rate, indicating a shift from adhesion to abrasion-based wear mechanisms.
- Material composition significantly affects tribological performance, with rigid materials exhibiting better wear resistance.
- Sliding speed influences wear behavior, where moderate speeds yield optimal friction and wear characteristics.

4.6 Implications and Practical Considerations

The findings provide valuable insights for designing PolyJet-printed components for wear-intensive applications, such as medical implants, tooling, and consumer products. Future work could focus on enhancing wear resistance through surface modifications, reinforcement additives, or post-processing techniques.

5. Conclusion and Future Work

5.1 Conclusion

This study investigated the tribological properties of PolyJet-printed digital materials under varying loading conditions (normal load and sliding speed) using a pin-on-disc tribometer. The key findings are summarized as follows:

- The coefficient of friction (CoF) decreased with increasing normal load due to enhanced surface conformity and third-body wear effects.
- Wear rate increased at higher loads (above 10 N), indicating a transition from mild adhesive wear to severe abrasive wear.
- Material composition played a crucial role in tribological performance, with rigid digital materials (e.g., VeroWhitePlus™) exhibiting superior wear resistance compared to elastomeric materials (e.g., Agilus30™).
- Sliding speed influenced wear mechanisms, where moderate speeds (100 mm/s) resulted in optimal wear performance, while excessive speeds (150 mm/s) led to thermal degradation.
- Surface analysis confirmed a shift in wear mechanisms from adhesive wear at low loads to abrasive wear at higher loads, with increased plastic deformation and material transfer.

These findings contribute to a deeper understanding of the wear and friction behavior of PolyJet-printed digital materials, providing guidance for optimizing their use in applications requiring high durability and low wear rates.

5.2 Future Work

To further enhance the tribological performance of PolyJet-printed materials, future research should focus on:

- Exploring the effects of reinforcement additives (e.g., nanoparticles, carbon fibers) to improve wear resistance.
- Investigating surface modification techniques, such as coating or chemical treatment, to enhance durability.
- Examining the influence of environmental conditions (e.g., humidity, temperature) on friction and wear properties.
- Extending the study to dynamic loading conditions, including impact and cyclic wear testing, to simulate real-world applications.
- Developing predictive models for wear behavior using machine learning and computational simulations.

By addressing these areas, future research can further optimize PolyJet-printed materials for high-performance applications in industries such as automotive, biomedical, and consumer goods.

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