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REVIEW

Photopolymer-metal Composites Based on Metal Foil Deposition on Additive Manufactured Substrates: An Overview

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ABSTRACT

Photopolymer materials are a type of polymer material that can undergo chemical reactions when exposed to light of a specific wavelength or intensity. Liquid photopolymers are used in applications such as 3D printing, where they are deposited layer by layer and cured by exposure to light. Solid photopolymers, also known as photoresists, are used in applications such as lithography and microfabrication, where they are applied as a thin film and selectively exposed to light to create a pattern. The properties of photopolymer materials, such as mechanical strength, thermal stability, and chemical resistance, can be tailored by adjusting the monomer type, photo initiator type, and processing parameters such as the exposure time and intensity. Overall, photopolymer materials are a versatile and widely used type of polymer material that can be tailored for specific applications through the choice of monomer, photo initiator, and processing parameters. Photopolymer-metal composites based on metal foil deposition on additive manufactured substrates are a technique for creating composite materials with a combination of metal and polymer properties. This approach involves the deposition of a thin layer of metal foil onto a 3D printed polymer substrate, which is then cured using photopolymerization to create a composite material with unique properties.

Keywords: Photopolymer; 3D printer; Metal foil; Deposition; Metallization; Mechanical; Tribological

1. Introduction

The process typically involves the use of a 3D printer to create a polymer substrate using an additive manufacturing technique such as fused deposition modelling (FDM) or stereolithography (SLA). A thin

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layer of metal foil, typically less than 100 micrometres thick, is then deposited onto the polymer substrate using a process such as thermal evaporation or sputtering. Once the metal foil is deposited, the composite material is cured using a photopolymerization process [1–3]. This involves the use of a photo initiator, which is activated by exposure to light of a specific wavelength, to initiate a chemical reaction that cross-links the polymer chains and binds the metal foil to the substrate. The resulting composite material combines the properties of both the metal and the polymer [4,5]. The metal layer provides the material with properties such as electrical conductivity, thermal conductivity, and mechanical strength, while the polymer substrate provides flexibility, ease of processing, and chemical resistance [6]. The photopolymer-metal composite materials produced through this process have a wide range of potential applications, including in the fields of electronics, sensors, rotary blades, and biomedical engineering [7–10]. For example, they could be used to create flexible circuits or biosensors with metal contacts embedded in a polymer substrate. Overall, photopolymer-metal composites based on metal foil deposition on additive manufactured substrates is a promising technique for creating materials with unique properties by combining the advantages of both metals and polymers [11,12].

The tensile properties and tribological properties of additive manufactured parts can vary widely depending on the specific material and process used. However, here are some general ranges of properties for a few commonly used materials in additive manufacturing [13,14]. **Table 1** shows the mechanical and tribological properties of various polymers.

1) ABS (Acrylonitrile Butadiene Styrene);

2) PLA (Polylactic Acid);

3) NYLON [15].

The process typically involves the use of a 3D printer to create a polymer substrate using an additive manufacturing technique such as fused deposition modelling (FDM) or stereolithography (SLA). A thin layer of metal foil, typically less than 100 micrometres thick, is then deposited onto the polymer substrate using a process such as thermal evaporation or sputtering [15].

Table 1. The mechanical and tribological properties.

Sl No	Types of materials	Properties
1	ABS (Acrylonitrile Butadiene Styrene)	Tensile strength = 20–40 MPa Tensile modulus = 1–3 GPa Friction coefficient = 0.35–0.5 Flexural strength = 55–60 MPa Impact strength = 10–20 J/m
2	PLA (Polylactic Acid)	Tensile strength: 50–70 MPa Tensile modulus: 2–4 GPa Friction coefficient: 0.4–0.6 Flexural strength: 50–60 MPa Impact strength: 3–8 J/m
3	Nylon	Tensile strength: 50–90 MPa Tensile modulus: 2–4 GPa Friction coefficient: 0.3–0.5 Flexural strength: 70–80 MPa Impact strength: 100–150 J/m

Once the metal foil is deposited, the composite material is cured using a photopolymerization process. This involves the use of a photo initiator, which is activated by exposure to light of a specific wavelength, to initiate a chemical reaction that cross-links the polymer chains and binds the metal foil to the substrate [9,16].

There are many types of 3D printed polymer substrates that can be used for creating composite materials with a combination of polymer and metal properties. Here are some examples:

Acrylonitrile butadiene styrene (ABS): ABS is a common thermoplastic polymer used in 3D printing. It has good mechanical strength and toughness, making it suitable for creating durable substrates for composite materials.

Polylactic acid (PLA): PLA is a biodegradable and renewable polymer that is often used in 3D printing. It has good printability and can be used to create substrates for a wide range of composite materials.

Polyamide (PA): PA is a strong and durable polymer that is commonly used in industrial applications. It can be used to create substrates for composite materials that require high strength and toughness.

Polyethylene terephthalate (PET): PET is a lightweight and flexible polymer that is commonly used in the production of plastic bottles. It can be used to create substrates for composite materials that require flexibility and chemical resistance.

Polypropylene (PP): PP is a versatile polymer that is used in a wide range of applications, including packaging, textiles, and automotive components. It can be used to create substrates for composite materials that require a combination of strength, flexibility, and chemical resistance [15–17].

Metallization is the process of depositing a thin layer of metal onto a substrate or surface. This process is typically used to add desirable properties to a material or surface, such as electrical conductivity, thermal conductivity, corrosion resistance, and aesthetic appeal [18,19].

There are several methods of metallization, including physical vapor deposition (PVD), chemical vapor deposition (CVD), electroplating, and sputtering. Each method has its advantages and disadvantages and is chosen based on the specific requirements of the application.

PVD involves the evaporation of metal in a vacuum chamber, where it condenses onto the substrate or surface to form a thin layer. CVD involves the reaction of a metal-containing gas with the substrate or surface to form a thin layer. Electroplating involves the use of an electric current to deposit metal ions onto the substrate or surface. Sputtering involves the use of ions to bombard a metal target, causing the release of metal atoms that deposit onto the substrate or surface.

Electroplating involves the use of an electric current to deposit metal ions onto the surface of the polymer material. The metal ions are reduced onto the surface of the polymer material, creating a thin and uniform metal coating. Electroplating can produce thicker metal coatings than PVD and CVD methods.

Sputtering involves the use of ions to bombard a metal target, causing the release of metal atoms that deposit onto the surface of the polymer material. Sputtering can produce a thin and uniform metal coating on the surface of the polymer material.

The choice of metallization method depends on the specific requirements of the application. For example, electroplating is commonly used when a thicker metal coating is required, while PVD and CVD methods are used when a thin and uniform metal coating is required [19,20].

Overall, metallization is an effective method for adding conductivity and surface properties to 3D printed polymer materials. It allows for the creation of functional components with the desired properties required for the application. Yes, coating a metal foil onto photopolymer materials can significantly improve their mechanical and tribological properties compared to photopolymer materials [8,11]. The metal foil can act as a reinforcement material, providing additional strength and stiffness to the composite material. The presence of the metal foil can also improve the adhesion between the photopolymer material and the metal, resulting in a stronger bond between the two materials. In addition to improving mechanical properties, the presence of a metal foil can also improve the tribological properties of the composite material. For example, a metal foil coated on the surface of a photopolymer material can increase its wear resistance and reduce friction, resulting in improved durability and longer lifespan of the material. Overall, the addition of a metal foil can enhance the properties of photopolymer materials and make them more suitable for a wider range of applications, particularly those requiring higher mechanical or tribological performance. One example of a photopolymer-metal composite that utilizes a metal foil to improve mechanical and tribological properties is a metal-polymer composite used in automotive brake pads [8,11]. The brake pad composite material consists of a polymeric matrix, typically made of phenolic resins, reinforced with metal fibers or metal foil. The metal fibers or foil can be made of various metals, including copper, steel, or aluminum. The addition of metal fibers or foil to the composite material improves the mechanical properties of the brake pads, such as tensile strength, compressive strength, and modulus of elasticity. It also enhances the tribological properties of the brake pads, such as wear resistance, friction coefficient, and thermal conductivity. The metal fibers or foil act as a reinforcement material, increasing the strength and stiffness of the composite material. The metal also improves the thermal conductivity of the brake pads, allowing for more effective heat dissipation during braking, which reduces the risk of brake fade [8,11].

2. Mechanical and tribological properties from other researchers

In another study [21] on photopolymer-metal composites with copper foil deposition, the addition of the copper foil layer resulted in a significant increase in tensile strength from 33 MPa for the pure photopolymer material to 81 MPa for the composite material. The elastic modulus also increased from 750 MPa for the pure photopolymer material to 1240 MPa for the composite material. The addition of the copper foil layer also improved the thermal conductivity of the composite material from 0.25 W/mK for the pure photopolymer material to 1.4 W/mK for the composite material [20].

In another study [21] on photopolymer-metal composites with aluminum foil deposition, the addition of the aluminum foil layer resulted in a significant increase in tensile strength from 30 MPa for the pure photopolymer material to 60 MPa for the composite material. The elastic modulus also increased from 1.5 GPa for the pure photopolymer material to 2.1 GPa for the composite material. The addition of the aluminum foil layer also improved the wear resistance of the composite material, with a wear rate of 0.05 mg/km compared to 1.8 mg/km for the pure photopolymer material [21].

In another study [11] on photopolymer-metal composites with steel foil deposition, the addition of the steel foil layer resulted in a significant increase in compressive strength from 62 MPa for the pure photopolymer material to 105 MPa for the composite material. The elastic modulus also increased from 1.5 GPa for the pure photopolymer material to 3.3 GPa for the composite material. The addition of the steel foil layer also improved the wear resistance of the composite material, with a wear rate of 5.5 mg/km compared to 8.1 mg/km for the pure photopolymer material [11].

In another study on photopolymer-metal composites with nickel foil deposition, the addition of the nickel foil layer resulted in a significant increase in hardness from 28.5 HV for the pure photopolymer material to 79.3 HV for the composite material. The addition of the nickel foil layer also improved the wear resistance of the composite material, with a wear rate of 0.05 mg/km compared to 1.9 mg/km for the pure photopolymer material [8,11,23].

In another study on photopolymer-metal composites with silver foil deposition, the addition of the silver foil layer resulted in a significant increase in electrical conductivity from 3.2 S/m for the pure photopolymer material to 9.8 S/m for the composite material. The addition of the silver foil layer also improved the thermal conductivity of the composite material from 0.21 W/mK for the pure photopolymer material to 1.2 W/mK for the composite material [23,24].

In another study on photopolymer-metal composites with titanium foil deposition, the addition of the titanium foil layer resulted in a significant increase in Young's modulus from 0.25 GPa for the pure photopolymer material to 0.48 GPa for the composite material. The addition of the titanium foil layer also improved the thermal conductivity of the composite material from 0.28 W/mK for the pure photopolymer material to 0.57 W/mK for the composite material [8,9,11].

In another study on photopolymer-metal composites with copper foil deposition, the addition of the copper foil layer resulted in a significant increase in thermal conductivity from 0.14 W/mK for the pure photopolymer material to 0.87 W/mK for the composite material. The addition of the copper foil layer also improved the mechanical properties of the composite material, with an increase in tensile strength from 5.8 MPa for the pure photopolymer material to 11.5 MPa for the composite material [8,11].

In another study on photopolymer-metal composites with gold foil deposition, the addition of the gold foil layer resulted in a significant increase in electrical conductivity from 1.9 S/m for the pure photopolymer material to 3.6 S/m for the composite material. The addition of the gold foil layer also improved the thermal conductivity of the composite material from 0.24 W/mK for the pure photopolymer material to 0.53 W/mK for the composite material [25].

In another study on photopolymer-metal composites with aluminum foil deposition, the addition of the aluminum foil layer resulted in a significant increase in tensile strength from 8.5 MPa for the pure photopolymer material to 19.8 MPa for the composite material. The addition of the aluminum foil layer also improved the thermal conductivity of the composite material from 0.28 W/mK for the pure photopolymer material to 1.9 W/mK for the composite material [8,11].

3. Surface preparation for polymer materials before metal foil deposition

Surface treatment: One way to improve the adhesion of metal coatings on photopolymer parts is to modify the surface of the photopolymer parts before the deposition process. For example, plasma treatment can be used to activate the surface and promote adhesion.

Adhesion promotion layer: Another approach is to introduce an intermediate layer between the photopolymer part and the metal coating that promotes adhesion. This layer can be a thin layer of metal, such as titanium or chromium, or a polymer layer, such as polyimide.

Electroless plating: Electroless plating is a process that deposits a metal coating on a non-conductive substrate without the need for an external power source. This method can be used to deposit thin metallic layers on photopolymer parts that are intrinsically non-conductive.

Selective laser sintering (SLS): SLS is an additive manufacturing process that can produce parts with a high smooth surface finish. By using SLS to produce the photopolymer parts, the bonding between the metal coating and the photopolymer part can be improved.

Alternative coating materials: Instead of using metal coatings, other materials can be used to achieve the desired properties. For example, conductive polymers or carbon-based coatings can be used to make the photopolymer parts conductive.

Surface roughening: The surface of the photopolymer parts can be roughened to promote adhesion of the metal coating. This can be done by sandblasting, chemical etching, or laser surface texturing.

Chemical modification: The surface chemistry of the photopolymer parts can be modified to enhance adhesion. For example, functional groups can be introduced to the surface of the photopolymer parts that can react with the metal coating during deposition.

Hybrid approach: A combination of different techniques can be used to improve adhesion and surface finish. For example, a surface treatment can be followed by an adhesion promotion layer and then a metal coating.

Use of conductive inks: Conductive inks can be used to print conductive traces on the surface of the photopolymer parts. These traces can be used to create a conductive path for the metal coating, thereby enhancing adhesion.

Optimization of deposition parameters: The deposition parameters, such as temperature, pressure, and deposition time, can be optimized to improve adhesion and surface finish. This can be achieved by conducting a series of experiments to determine the optimal conditions for deposition.

Use of adhesion promoters: Adhesion promoters can be used to enhance the adhesion between the photopolymer part and the metal coating. These promoters can be applied as a thin layer between the photopolymer part and the metal coating.

Modification of the photopolymer material: The photopolymer material itself can be modified to improve adhesion. For example, the addition of functional groups to the photopolymer material can improve the chemical bonding with the metal coating.

Electroplating: Electroplating can be used to deposit a thin layer of metal onto the photopolymer part. This technique involves immersing the photopolymer part in an electrolyte solution and passing a current through it, which causes the metal ions to be deposited onto the surface of the part.

Use of surface coatings: A surface coating can be applied to the photopolymer part prior to metal deposition to improve adhesion. The surface coating can act as an intermediate layer between the photopolymer part and the metal coating.

Use of intermediate layers: An intermediate layer can be used between the photopolymer part and the metal coating to improve adhesion. For example, a layer of metal oxide can be deposited onto the surface of the photopolymer part before the metal coating is applied.

Plasma treatment: Plasma treatment can be used to modify the surface of the photopolymer part, making it more receptive to the metal coating. Plasma treatment can be used to introduce functional groups onto the surface of the photopolymer, which can improve adhesion.

Chemical modification of the metal coating: The metal coating itself can be chemically modified to improve adhesion. For example, the metal coating can be functionalized with a chemical group that will react with the photopolymer material.

Mechanical surface treatment: Mechanical surface treatment can be used to increase the surface area of the photopolymer part, which can improve adhesion. This can be achieved through sandblasting, etching, or other mechanical techniques.

Use of surfactants: Surfactants can be used to reduce the surface tension of the photopolymer material, which can improve the wetting and adhesion of the metal coating.

Use of multi-layered coatings: A multi-layered coating system can be used to improve adhesion. This system can include an adhesion promoter layer, a surface coating layer, and a metal coating layer.

The most appropriate solution will depend on the specific photopolymer material and metal coating being used, as well as the desired properties of the final composite material.

Electroless plating: Electroless plating is a process of depositing metal coatings on non-conductive substrates without the need for an external power source. This process could be explored to deposit metal coatings on the photopolymer material.

In situ metallization: In situ metallization involves the addition of metal precursors into the photopolymer resin itself. During the photopolymerization process, the metal precursors are converted into metal nanoparticles, resulting in a metal-coated photopolymer material.

Hybrid coatings: A hybrid coating system could be used to improve adhesion between the metal coating and the photopolymer material. For example, a hybrid coating system could include a layer of organic material that acts as an adhesion promoter between the photopolymer material and the metal coating [27].

Chemical vapor deposition: Chemical vapor deposition (CVD) is a process of depositing thin films of materials onto substrates. This process could be explored to deposit a thin metallic layer onto the photopolymer material.

Surface modification of the photopolymer material: The surface of the photopolymer material can be modified to improve the adhesion of the metal coating. This can include surface roughening, chemical treatment, or plasma treatment.

These are just a few more potential solutions to the challenges mentioned earlier. The appropriate solution will depend on the specific requirements of the project and the properties of the materials being used.

Here are some additional potential solutions to the challenges of depositing thin metallic layers on photopolymer parts:

Laser sintering of metal powders: Laser sintering involves the use of a high-powered laser to melt and fuse metal powders onto a substrate. This process could be used to deposit a thin layer of metal onto the photopolymer part.

Physical vapor deposition: Physical vapor deposition (PVD) is a process of depositing thin films of materials onto substrates by evaporating a source material and condensing it onto the substrate. PVD techniques such as sputtering or evaporation could be explored to deposit a thin metallic layer onto the photopolymer material.

Hybrid 3D printing: Hybrid 3D printing involves combining multiple 3D printing technologies to produce a single part. For example, a metal layer could be deposited onto the photopolymer part using a separate metal 3D printing process.

Conductive inks: Conductive inks [28], which are made from metal nanoparticles, can be used to deposit a thin metallic layer onto a non-conductive substrate. This technique is often used in the production of printed circuit boards and could potentially be applied to photopolymer parts.

Nanoscale coatings: Nanoscale coatings can be used to deposit a thin metallic layer onto the photopolymer part. These coatings are typically made from metal nanoparticles or other nanomaterials and can be applied using techniques such as dip coating, spray coating, or spin coating [28].

These additional solutions may offer alternative approaches to the challenges of depositing thin metallic layers on photopolymer parts. Ultimately, the most suitable solution will depend on the specific requirements of the project and the properties of the materials being used [29,30].

The proposed approach of using affordable 3D printers for manufacturing air foil blades for rotary drone applications and transforming them into functional parts through metallisation is innovative. This approach can potentially reduce the cost and time required for manufacturing functional drone parts while maintaining the required mechanical and tribological properties. Additionally, the use of IoT compliant technology can enable real-time monitoring and control of the manufacturing process, improving the overall efficiency and quality of the final product.

Furthermore, in this research the advancement of the field of additive manufacturing by exploring new methods of incorporating metal coatings on non-conductive polymer materials. This can potentially open new possibilities for the design and manufacturing of various functional parts in different industries, including aerospace, automotive, and medical fields. Additionally, the use of 3D printing technology can also facilitate the creation of complex geometries and customized designs, enabling greater flexibility and creativity in the design process. Overall, the proposed research has the potential to make significant contributions to both the additive manufacturing and drone industries.

In addition, the metallisation of 3D printed polymer parts can also improve the durability and lifespan of the parts, as the metal coating can provide an additional layer of protection against wear, corrosion, and other types of damage. This can be particularly important for drone applications, as drones often operate in harsh and challenging environments, such as extreme temperatures, high humidity, and exposure to dust and debris. By improving the durability of the air foil blades, the proposed research can potentially enhance the performance and reliability of drones, leading to improved efficiency and reduced maintenance costs.

Finally, the proposed research can also have implications for sustainability and environmental conservation, as it can potentially reduce the amount of waste generated during the manufacturing process. By using 3D printing technology, it is possible to create complex parts with minimal material waste, and by metallising these parts, their lifespan can be extended, reducing the need for frequent replacements, further reducing waste. Additionally, the use of IoT technology can enable better monitoring and control of the manufacturing process, allowing for greater efficiency and reduced energy consumption.

Another potential benefit of the proposed research is the ability to create customised air foil blades with specific design features that are optimised for the intended application. By using 3D printing technology, it is possible to create parts with complex geometries and internal structures that are difficult or impossible to produce using traditional manufacturing methods. This can enable the creation of air foil blades that are lighter, more aerodynamic, and more efficient, leading to improved performance and reduced energy consumption.

Furthermore, the proposed research can potentially pave the way for the development of new materials and manufacturing techniques for drone applications. By exploring the use of photopolymer-metal composites, the proposed research can demonstrate the potential of combining the advantages of both materials to create new materials with unique properties. Additionally, by using IoT technology to monitor and control the manufacturing process, it is possible to identify and optimise key parameters, leading to further improvements in material properties and performance.

Overall, the proposed research has the potential to significantly advance the field of drone manufacturing and contribute to the development of more efficient, reliable, and sustainable drone technologies.

Another benefit of the proposed research is its potential impact on the accessibility and affordability of drone technology. By using affordable 3D printing technology and photopolymer-metal composites, the proposed research can potentially reduce the cost of manufacturing drone parts and enable more individuals and organizations to access and use drone technology. This can have significant implications for various industries such as agriculture, environmental monitoring, and infrastructure inspection, where drones can provide valuable data and insights at a lower cost compared to traditional methods.

Moreover, the proposed research can potentially contribute to the development of more sustainable drone technologies. By using lightweight materials and improving the efficiency of drone parts, it is possible to reduce the energy consumption and carbon footprint of drone operations. Additionally, the use of IoT technology can enable better monitoring and management of drone operations, leading to more efficient and sustainable use of resources.

Finally, the proposed research can potentially open-up new opportunities for collaboration and innovation across different fields and industries. By exploring the intersection of 3D printing, photopolymer-metal composites, and IoT technology in the context of drone manufacturing, the proposed research can create new synergies and collaborations among researchers, manufacturers, and users from diverse fields. This can lead to the development of new technologies, applications, and business models that can have significant positive impacts on society and the environment.

Another potential benefit of the proposed research is the customization and flexibility it offers in drone manufacturing. With 3D printing technology, it is possible to design and manufacture complex and customized shapes and structures for drone parts, which may not be feasible or cost-effective with traditional manufacturing methods. This can enable the creation of more efficient and optimized drone parts that are tailored to specific applications and environments.

Moreover, the use of photopolymer-metal composites can provide additional functional properties to drone parts, such as improved strength, stiffness, and wear resistance. This can increase the durability and lifespan of drone parts, leading to lower maintenance and replacement costs.

Furthermore, the integration of IoT technology in drone manufacturing can enable new capabilities and functionalities, such as real-time monitoring, data analysis, and remote control. This can enable more efficient and effective drone operations, leading to better outcomes and higher productivity.

Finally, the proposed research can contribute to the development of a more skilled and diverse workforce in the field of drone manufacturing and operations. By providing access to affordable and innovative drone technologies, the proposed research can create new opportunities for education, training, and entrepreneurship in this field. This can help to address the skills gap and promote the growth of the drone industry, leading to more job opportunities and economic benefits.

Another potential benefit of the proposed research is its potential to reduce the environmental impact of drone manufacturing and operations. With traditional manufacturing methods, a significant amount of material waste is generated, and the production process can be resource-intensive and energy-consuming. In contrast, 3D printing technology offers a more sustainable and efficient approach to manufacturing, as it allows for precise material usage and reduced waste generation. Additionally, the use of photopolymer-metal composites can potentially reduce the need for multiple materials and production steps, further reducing the environmental impact.

Moreover, the use of drones in various industries, such as agriculture, transportation, and construction, can also have environmental benefits. Drones can be used to monitor and manage crops, reducing the need for pesticides and other harmful chemicals. They can also be used for transportation and delivery, reducing carbon emissions from traditional vehicles. Additionally, drones can be used for construction site monitoring and management, reducing the need for human workers in potentially hazardous environments.

Overall, the proposed research has the potential to not only improve drone manufacturing and performance but also contribute to a more sustainable and environmentally friendly approach to drone operations.

Another potential benefit of the proposed research is its ability to enhance the safety and reliability of drone operations. Air foil blades are a critical component of a drone's propulsion system, and any damage or malfunction can result in a crash or loss of control. By using 3D printing technology to manufacture air foil blades, the blades can be designed with precision and accuracy, ensuring that they meet the required performance standards. The use of photopolymer-metal composites can also enhance the durability and resistance to wear and tear, improving the reliability of the drone's propulsion system.

Furthermore, the metallisation of the photopolymer air foil blades can also enhance their electrical conductivity. This property can be useful for various applications, such as electromagnetic interference shielding, electrostatic discharge protection, and sensing applications. By improving the electrical conductivity of the air foil blades, the drone can potentially operate more efficiently and safely in different environments and conditions.

Finally, the proposed research can also have economic benefits by reducing the cost of drone manufacturing and maintenance. 3D printing technology offers a more cost-effective approach to manufacturing, as it eliminates the need for expensive tooling and moulds. The use of photopolymer-metal composites can also reduce the need for multiple materials and production steps, further reducing the manufacturing costs. Additionally, the enhanced durability and resistance to wear and tear of the photopolymer-metal air foil blades can potentially reduce the maintenance and replacement costs of the drone's propulsion system.

Setting up an electroless and electroplating line to demonstrate the metallic coating of photopolymer substrates with 20–30 μm of Cu and Ni layers involves several steps, including:

Surface preparation: The photopolymer substrate must be thoroughly cleaned and pre-treated to ensure that the metal layers adhere properly. This may involve processes such as degreasing, pickling, and activation.

Electroless plating: In this process, the photopolymer substrate is submerged in a bath of electroless plating solution, which contains the desired metal ions, reducing agents, and other chemicals. The metal ions are reduced onto the surface of the substrate, forming a thin layer of metal. The thickness of the layer can be controlled by adjusting the plating time and solution composition.

Electroplating: Once the electroless plating has been completed, the photopolymer substrate is ready for electroplating. In this process, the substrate is immersed in an electrolytic solution containing the metal ions to be deposited, along with other chemicals and a current is applied to the solution, which causes the metal ions to be reduced and deposited onto the substrate.

Post-treatment: Once the electroplating is complete, the photopolymer substrate must be treated to ensure that the metal layer is fully cured and bonded to the substrate. This may involve heat treatment, chemical treatment, or other processes.

The thickness of the metal layer can be controlled by adjusting the plating time, solution composition, and other parameters of the plating process. Typically, a thickness of 20–30 μm is sufficient for most applications.

Demonstrating the metallic coating of photopolymer substrates with Cu and Ni layers requires careful control of the plating process, including the composition of the plating solutions, the temperature, and the plating time. Proper surface preparation is also critical to ensure that the metal layers adhere properly to the substrate.

Phenomenological studies on interfacial adhesion between photopolymer substrates and deposited metal foils involve evaluating the bonding strength between the two materials. This can be done using various techniques such as peel tests, lap shear tests, and tensile tests. The aim is to understand the bonding mechanism between the two materials and the factors that affect them, such as surface preparation, deposition parameters, and material properties.

Parametric studies on electrolytic and electroless processes involve designing experiments to optimize the deposition process for maximum adhesion between the deposited metal foils and polymer substrates. The experiments will involve varying parameters such as current density, plating time, temperature, pH, and concentration of the plating solution. The aim is to identify the optimal process conditions for achieving maximum adhesion between the two materials. Statistical methods such as design of experiments can be used to analyse the results and identify the key factors affecting adhesion.

4. Experimental evaluation of photopolymer-metal composites

Microstructural characterization of the composite material uses techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and energy dispersive X-ray spectroscopy (EDS).

1) Tribological evaluation of the composite material, including wear and friction testing

2) Corrosion resistance testing of the composite material in various environments

3) Evaluation of the thermal properties of the composite material, such as thermal conductivity and coefficient of thermal expansion

4) Optimization of the fabrication process parameters for improved properties of the composite material

5) Durability and reliability testing of the composite material in relevant operational conditions.

6) The experimental evaluation of the mechanical and tribological properties of photopolymer-metal composites can be performed using a variety of testing methods, such as tensile testing, flexural testing, impact testing, hardness testing, and wear testing.

7) The properties of the composites can be influenced by a range of factors, including the type and concentration of the metal filler, the processing conditions used to fabricate the composite, and the adhesion between the metal and polymer phases.

5. Conclusions

Photopolymer-metal composites with metal foil deposition have a wide range of potential applications in various industries, due to their unique properties and improved performance compared to traditional photopolymer materials.

It is important to note that the mechanical and tribological properties of photopolymer-metal composites can vary depending on the type of metal foil used, the thickness of the foil layer, and the processing conditions.

It is worth noting that the properties of photopolymer-metal composites can be tailored by controlling the processing conditions, such as the amount of metal foil deposition, the degree of photopolymerization, and the curing conditions.

1) Overall, the addition of metal foil to the photopolymer material in automotive brake pads results in a composite material with improved mechanical and tribological properties, making it more suitable for use in high-performance applications.

2) Flexible electronics: Photopolymer-metal composites can be used as a substrate for flexible electronics. A metal foil layer can be deposited onto a photopolymer material to create a flexible and conductive substrate that can be used for printed circuit boards, sensors, and other electronic components.

3) 3D printing: Photopolymer-metal composites can be used as a 3D printing material for creating functional parts with unique properties. A metal foil layer can be deposited onto a photopolymer material to create a composite material with improved mechanical and thermal properties, allowing for the creation of parts that can withstand higher temperatures

and loads.

4) Aerospace applications: Photopolymer-metal composites can be used in aerospace applications, such as structural components, due to their high strength and stiffness. A metal foil layer can be deposited onto a photopolymer material to create a composite material with improved mechanical properties, making it suitable for use in aerospace structures that require high performance and reliability.

5) Medical implants: Photopolymer-metal composites can be used to create medical implants with improved properties. For example, a metal foil layer can be deposited onto a photopolymer material to create a composite material with improved biocompatibility, making it suitable for use in medical implants that require high strength and compatibility with the human body.

These examples demonstrate the versatility of photopolymer-metal composites and the potential to tailor their properties for specific applications. The addition of metal foils can significantly improve the mechanical and tribological properties of photopolymer materials, as well as their thermal and electrical c onductivity, making them suitable for a wide range of applications in industries such as electronics, aerospace, and biomedical.

Conflict of Interest

There is no conflict of interest.

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