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3D-PRINTED STAINLESS STEEL ELECTRODES FOR ADVANCING MEMS MICROBIAL FUEL CELLS TOWARD SUSTAINABLE ON-CHIP ENERGY

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ABSTRACT

This study introduces a stainless steel microbial anode fabricated via advanced laser powder bed fusion, marking a transformative step in microbial fuel cell (MFC) technology. By leveraging this cutting-edge metal 3D printing approach, we achieve a 3D microporous structure with superior electrical conductivity, outstanding corrosion resistance in aquatic environments, robust mechanical strength, and adaptability for surface modification—essential attributes for sustainable, high-performance MFCs. The assembled MFC demonstrates unparalleled power output, along with exceptional durability and stability over multiple cycles, outperforming existing MFCs based on alternative 3D-printed substrates. This advancement not only solidifies the role of MFCs as a sustainable energy solution for powering on-chip electronics but also opens new avenues for scalable, cost-effective bioelectronic systems that align with the demands of next-generation technology.

KEYWORDS

Microbial fuel cells; Stainless steel; 3D printing; On-chip power source; Laser powder bed fusion

INTRODUCTION

Microbial fuel cells (MFCs) have emerged as a promising sustainable technology capable of converting waste organic materials into valuable electricity through microbial metabolic activities [1]. By harnessing bioenergy from organic waste, MFCs offer not only a renewable energy source but also environmental benefits by reducing pollutants [2]. The miniaturization of MFCs has unlocked revolutionary applications in powering portable devices and on-chip electronics, where traditional power sources are often impractical [3, 4]. In particular, MEMS MFCs present an ideal platform for integration into other MEMS or miniaturized electronic systems as compact and sustainable power sources [5-7]. Despite their potential, previously reported MEMS MFCs fabricated using various microfabrication techniques have exhibited limited performance due to their predominantly two-dimensional platforms and a lack of scalability, robustness, and reusability. A significant challenge lies in the microfabrication of the anode—the component that houses living bacterial cells and critically determines the MFC's performance [8-10]. Traditional methods have struggled to meet essential requirements for the anode, such as optimal porosity, high electrical conductivity, and structural stability, hindering the overall efficiency and applicability of MEMS MFCs.

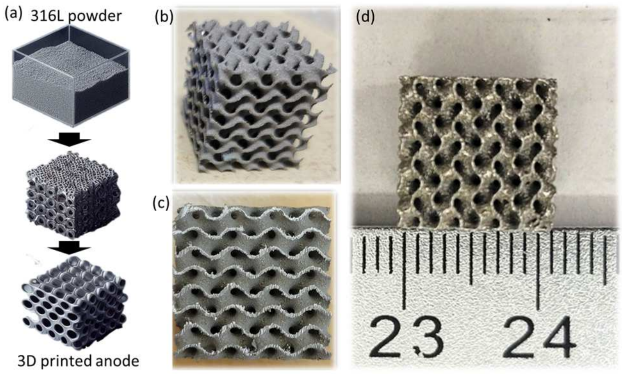

Figure 1: (a) 3D printing process of the stainless steel anode, (b) Image of the 3D-printed cubic anode, (c) Close-up of one surface of the cubic structure, (d) Image of the anode with dimensional specifications.

Recently, 3D printing has emerged as a transformative approach to overcome many limitations of traditional fabrication methods [11-14]. It allows for the creation of complex, three-dimensional structures with precise control over geometry, enhancing the efficiency and scalability of MFCs. Notably, 3D printing enables meticulous control over anode architecture, facilitating ideal porosity and increased surface area to support bacterial attachment and growth. However, the 3D printing of MFCs still faces material-related challenges. Printed anodes are often restricted to polymers with low conductivity and limited microbial electron transfer efficiency, as well as reduced mechanical strength and durability. These materials also tend to exhibit short-term stability in liquid environments and are challenging to reuse, presenting obstacles to the long-term performance and practical application of 3D-printed MFCs.

In this work, we introduce a novel approach by employing a 3D-printed stainless steel anode for MFCs. Stainless steel is renowned for its high electrical conductivity, excellent corrosion resistance in aquatic environments, mechanical strength, stability, cost-effectiveness, and potential for surface modification [15]. Moreover, its outstanding biocompatibility supports efficient microbial metabolic activity and enhances electron transfer processes. While stainless steel has been extensively explored as an anode material in MFCs [16, 17] —with its excellence proven in numerous studies—its application in 3D printing for MFC anodes has not been demonstrated until now. This study showcases the feasibility of 3D printing stainless steel anodes and demonstrates their exceptional performance in MFC applications. By leveraging the advantages of 3D printing technology and the superior properties of stainless steel, we address the critical challenges in anode fabrication for MEMS MFCs.

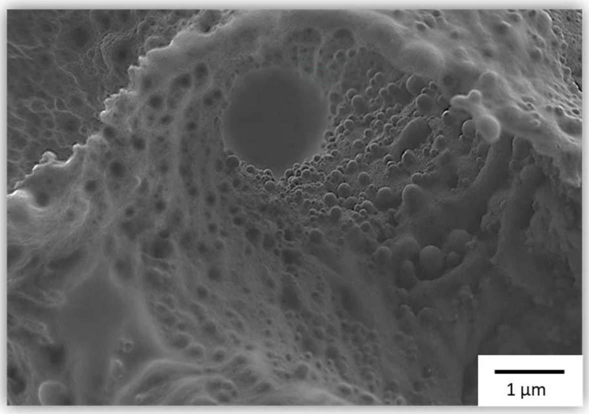

Figure 2: SEM image displaying bacterial cells embedded within the porous structure of the stainless steel anode.

MATERIALS AND METHODS

Preparation of Bacterial Inoculum

Bacillus subtilis endospores were employed as dormant biocatalysts for the MFC due to their resilience and durability under extreme conditions, allowing them to withstand all preparation steps prior to power generation [18, 19]. The vegetative *B. subtilis* cells were sourced from the American Type Culture Collection (ATCC). To induce sporulation, the bacteria were incubated at 37°C on nutrient-depleted agar plates for 48–72 hours, until endospore formation was confirmed microscopically by the presence of refractile structures. Following incubation, sterile distilled water was added to the plates, and the surface was gently scraped to release both spores and any remaining vegetative cells. The resulting suspension was collected in sterile centrifuge tubes and centrifuged at 4,000 rpm for 10 minutes to separate the spores. The supernatant was carefully decanted, leaving a spore pellet at the bottom of the tube, which was subsequently resuspended in sterile distilled water and thoroughly washed to ensure a pure spore preparation.

Configuration and Operating Principle of the MFC

MFCs are composed of an anode, a cathode, and a proton exchange membrane positioned between them [3-5]. In this setup, endospores are pre-loaded into a porous stainless steel anode cube. As shown in Figure 2, scanning electron microscope (SEM) images reveal densely packed spores embedded within the anode's porous structure. When a specific nutrient germinant containing the amino acids L-valine, L-alanine, and a mixture of L-asparagine, glucose, fructose, and potassium chloride (AGFK) is introduced, spore germination is triggered, activating the MFC [18, 19]. Upon germination, the vegetative cells initiate metabolic processes, breaking down organic matter and producing protons and electrons. Protons move through the proton exchange membrane to the cathode, while electrons flow externally through a circuit, powering a load before returning to the cathode. At the cathode, the electrons and protons recombine with oxygen to produce water, completing the reaction and sustaining the MFC's power generation.

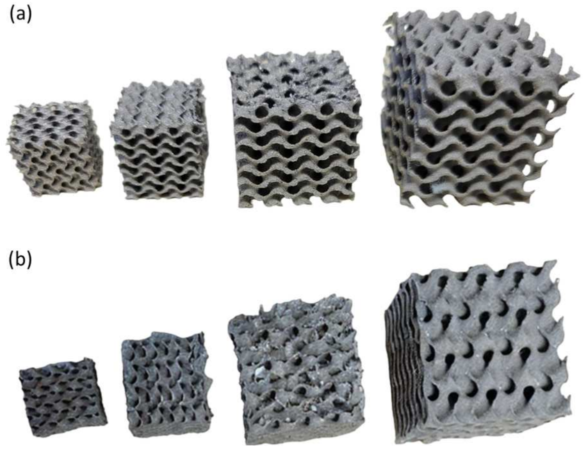

Figure 3: Images of 3D-printed stainless steel structures in various sizes and shapes.

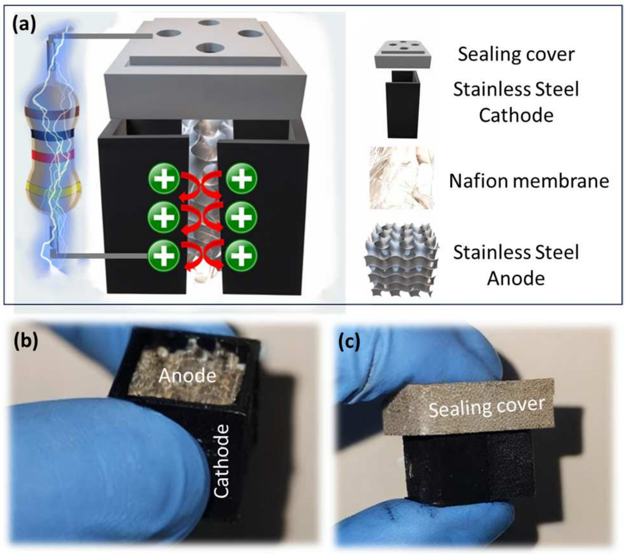

Figure 4: (a) Conceptual illustration of the assembled MFC configuration, detailing its individual components; (b) Image of the assembled MFC without the sealing cover; (c) Image of the assembled MFC with the sealing cover in place.

3D Printing of Stainless Steel

Laser powder bed fusion (LPBF), an advanced metal 3D printing technology, was employed to fabricate stainless steel anodes with tailored porosity and surface structures, enhancing microbial attachment and electron transfer efficiency in microbial fuel cells (MFCs) [20, 21]. Using 316L stainless steel powder, 3D anodes were produced on an XM200G LPBF printer (Xact Metal, PA, USA) equipped with a 200 W laser. Key printing parameters were optimized to achieve high-quality prints, including a laser power of 180 W, scanning speed of 400 mm/s, layer thickness of 30 µm, hatch spacing of 100 µm, and an Argon gas atmosphere to maintain an inert environment, resulting in 3D microporous structures with diverse sizes and shapes (Figure 3).

Fabrication of the MFC

To prepare the cathode, the 3D-printed stainless steel structure was coated with a platinum-carbon (Pt/C) catalyst via a dip-coating process. The cathode was submerged in a Pt/C dispersion with Nafion as a binder to improve both adhesion and conductivity. Dimethyl sulfoxide (DMSO) was added to stabilize the catalyst dispersion. After coating, the cathode was oven-dried at 60°C for 30 minutes. This process was repeated several times to achieve a uniform catalyst layer. Finally, the coated cathode underwent a curing phase at 100°C for 1 hour, ensuring complete solvent evaporation and optimal catalytic performance.

For the assembly of the MEMS MFC, a commercial Nafion 117 membrane was sandwiched between the prepared anode and Pt/C-coated cathode (Figure 4a). To ensure a secure bond and alignment, the assembled components were subjected to heat treatment. This process enabled strong adhesion between the membrane and electrodes, preventing any potential movement or misalignment during operation and enhancing ionic conductivity across the membrane for efficient electron transfer. The final configuration was optimized to maintain close contact between components, ensuring robust performance and long-term stability of the MFC (Figure 4b).

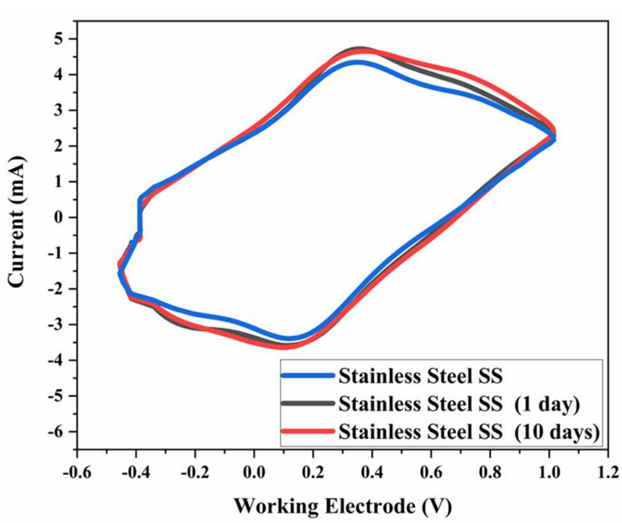

Figure 5: Cyclic voltammetry curves of the reused SS electrode embedded with bacteria over different days.

RESULTS AND DISCUSSION

The 3D-printed anode demonstrated exceptional stability and reusability, retaining its bioelectrochemical activity with adhered *B. subtilis* cells over extended periods without signs of degradation. This stability was evident in its cyclic voltammetric profiles, which displayed consistent and stable electrochemical responses immediately after fabrication, as well as after 1 day and 10 days of continuous operation (Figure 5). The stable profile suggests robust adhesion and biofilm formation of *B. subtilis* on the anode surface, which is critical for sustained electron transfer and bioelectrochemical performance. Additionally, the lack of any significant shifts in redox peaks over time underscores the electrode's resilience to potential biofouling or material fatigue, positioning it as a durable, high-performance component for long-term applications in MFCs.

The electrical performance of the assembled MFC (Figure 6a) was evaluated using a data acquisition system (DI-4108U, DataQ) across a range of external resistors. The polarization curve (I-V profile) and power output (I-P profile) were generated by recording voltage drops at selected external resistors and calculating the corresponding current and power values (Figure 6b). The MFC achieved a maximum power output of 127 µW and a peak current of 750 µA, both of which represent remarkably high performance compared to other miniature MFCs constructed on alternative substrates such as paper, polymers, and carbon (Figure 6c) [22-24]. Additionally, the 3D-printed stainless steel anode demonstrated excellent durability and stability, maintaining its performance over multiple reuse cycles within the MFC (Figure 6d). This robust performance underscores the advantages of the 3D-printed stainless steel anode, offering enhanced current and power generation along with long-term operational stability, marking a significant advancement in the development of high-efficiency, reusable miniature MFCs.

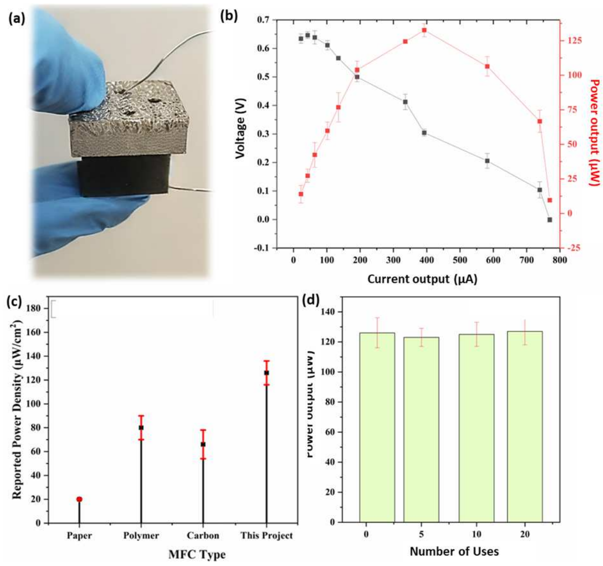

Figure 6: (a) Photograph of the fully assembled MFC. (b) Polarization curve and power output profile of the MFC, illustrating its I-V and I-P characteristics. (c) Comparative analysis of power density between the MFC on 3D-printed stainless steel and other material-based MFCs, demonstrating the superior performance of our device. (d) Power output stability of the MFC across multiple cycles, highlighting its durability and reusability in sustained bioelectrochemical applications.

CONCLUSION

This study presents an innovative 3D-printed stainless steel anode designed for MEMS-based MFCs. The anode's 3D microporous structure offers precise control over pore size and shape, providing excellent stability, reusability, and biocompatibility. It effectively retained bioelectrochemical activity with bacterial catalysts, showing no signs of degradation. Additionally, the 3D-printed stainless steel structure facilitated straightforward surface modification with cathodic catalysts. The assembled MFC achieved exceptionally high-power output and demonstrated remarkable durability and stability over multiple cycles, outperforming previously reported miniature MFCs using alternative anode materials.

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