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Electrochemical additive manufacturing of interdigitated structures using a multi-anode system with independently-controlled anodes

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Abstract

Interdigitated parts are used across a multitude of engineering applications. The overlapping, intertwined structures pose a challenge for fabrication using conventional additive manufacturing techniques, especially at small size scales. Electrochemical additive manufacturing (ECAM) has been shown to successfully create overhanging parts at the small scale without reliance on support structures. This study extends the ECAM capabilities into demonstration of the fabrication of interdigitated parts by the use of a multi-anode electrochemical additive manufacturing system. The ECAM process is operated by a tool head consisting of multiple anodes independently controlled by individual channels on an in-house-built multipotentiostatic system. Each anode is independently switched into active (anodic) or inactive (open-circuit) mode using a predefined, coded pattern controlling the custom electronics. While each tool is in anodic mode, its current contribution into the overall deposition process is tracked independently as well. Each independent tool can deposit material extending from regions deposited by itself or neighboring tools. The entire multi-head tool is controllably moved by a 3-axis translation system. An interdigitated comb geometry relevant to practical engineering applications is fabricated using this system. This geometry is built using a parallelized voxel-by-voxel tool path with characteristic electrode activation patterns at each position of the tool head. It was found that a purely closed-loop control with no time limit yielded a qualitatively better geometry than a control system with a 10-minute time limit applied. This study overall demonstrates the working principle of a multi-anode system and its ability to fabricate parts interdigitated structures. This study therefore advances the capabilities of ECAM as a valuable additive manufacturing process that can fabricate a variety of challenging parts for relevant engineering applications.

Keywords: electrochemical deposition; interdigitated structure; multiple-anode

1. Introduction

This study introduces the feasibility of electrochemical additive manufacturing in the fabrication of interdigitated structures for various engineering applications. The relevant applications of interdigitated parts are discussed, followed by current fabrication challenges and expected advantages of fabricating the parts using a multi-anode electrochemical additive manufacturing process.

Nomenclature

d	Interdigital distance
n	Number of electrode fingers
w	Digit width
r	Ratio of digit width to interdigital distance (w/d)

1.1. Interdigitated structures and applications

Interdigital structures are one of the most widely-used geometries across a wide variety of sensing applications, including those in medicine, environment, and industry. The use of various sensing and monitoring technologies has been rapidly growing in recent years, resulting in an increase in the exploration of varying sensor geometry designs and demand for corresponding fabrication techniques [1].

Electrochemical energy storage is another field in which interdigital structures are used, in parts such as batteries and supercapacitors. In contrast to flat plates, interdigitated geometries allow for increased energy storage density over small sizes [2].

Interdigitated structures are also present in micro and millimeter wave components for communications; operation at higher frequencies demands fabrication of parts at finer resolutions [3].

1.2. Challenges with existing fabrication methods of interdigital structures

Interdigital structures are typically small-sized and low-cost. A wide variety of methods exist to fabricate such parts; however, each technique is associated with its own unique challenges.

Silicon-based MEMS techniques require costly and labor-intensive fabrication procedures in cleanroom facilities. Laser-based cutting of flexible sensors involves thermal effects, which may compromise the geometry and material integrity of the output parts. Screen-printing techniques introduce several challenges, including: interference among multiple digits and constituent elements within a small area, required assembly steps, difficulty in repair of errors, and effective transfer of conductive ink during the fabrication process. Inkjet printing challenges include degradation of printed material under heat treatment and pressure, as well as unintended capacitances occurring in between printed layers [1].

Various additive manufacturing techniques have also been used to print interdigitated parts, but also have their own shortcomings. Stereolithography and selective laser sintering introduce high costs that make the processes not feasible for practical use. Ink-based methods are limited due to the trade-off between rheological properties of the ink and the necessity to incorporate the appropriate active materials for the electrodes; the use of additives can compromise the performance in electrochemical applications, and some active electrode materials cannot be incorporated in inks. The resolution of the printed parts is also limited to the mesoscopic size scale [2].

1.3. Electrochemical additive manufacturing

This study introduces the feasibility of manufacturing interdigitated structures using the electrochemical additive manufacturing (ECAM) process in a manner that avoids the previously-mentioned fabrication challenges. ECAM is an emerging, nontraditional additive manufacturing process which makes use of localized electrochemical deposition as the material addition method to fabricate complex, three-dimensional parts. The nature of the ECAM process presents several advantages in the fabrication of interdigitated structures. The depositing atoms directly bind to the already-deposited structure in a single physical process [4]. This means that unwanted capacitances between deposited layers and labor-intensive, multi-step procedures are avoided [1]. The room-temperature operation of ECAM avoids thermal defects and yields parts with relatively low residual stress [5]. The computer-controlled, voxel-by-voxel fabrication process allows for complex 3D structures to be built avoiding the need for assembly or removal of support structures [6]. The applied signal can also directly control the porosity [7] and localization [8] of the output deposit, which are especially desirable in parts built for electrochemical applications [2].

1.4. Deposition using multiple electrodes

The majority of ECAM studies have been performed using a single-tool configuration [9-12]. However, interdigitated structures introduce numerous parallel, side-by-side, repeating patterns. While these may be fabricated using a single-tool configuration, the nature of the geometry of these parts introduces the opportunity for straightforward parallelization of deposition by the use of multiple tools working simultaneously.

In contrast to single-tool deposition, multiple-tool deposition enables several advantages in the fabrication of interdigitated electrode structures. First, the simultaneous deposition of voxels in parallel results in an overall reduction of build time. Second, the nature of interdigitated structures – involving several interlocking digits in a confined space – does not allow for straightforward tool paths using one tool; it is not possible for the tool to build one separate entity and then the other in series. Instead, the tool must maneuver from one entity to the other mid-build, which introduces extra tool path complication, maneuvering time, risk of part damage, and risk of discontinuities in the geometry. In contrast, building such parts using a parallel tool system allows for straightforward, continuous tool paths.

Electrochemical additive manufacturing has been operated in a multi-anode configuration using a finely-spaced, individually-addressable multi-anode matrix [13]. However, such work has focused on the deposition of layered bulk structures and involves the costly, intensive fabrication of a multi-anode matrix head with a limited lifespan [14]. The number of anodes in such a head may also be excessive for the construction of an interdigitated part with a finite amount of separate electrode digits. The head itself may also limit electrolyte flow and maneuverability during the build of delicate interdigitated structures.

Therefore, this study focuses on a straightforward, low-cost tool head with a limited amount of electrodes specifically for the deposition of interdigitated structures. This enables fabrication of these repeating structures in a more efficient, low-cost manner.

2. Methods

2.1. Multi-electrode head

Electrochemical additive manufacturing was performed using a multi-electrode head as illustrated in Figure 1. Two 250 µm diameter Pt-Ir wire anodes were used as the anodic tools. The diameter of the deposition beneath each tool was approximately 300 µm, and this was defined as the lateral extent of a single voxel. The tools were spaced apart by approximately 2.5 voxels, leaving a gap of 1.5 equivalent voxels in between the parallel deposits. An interelectrode gap of 45 µm was used.

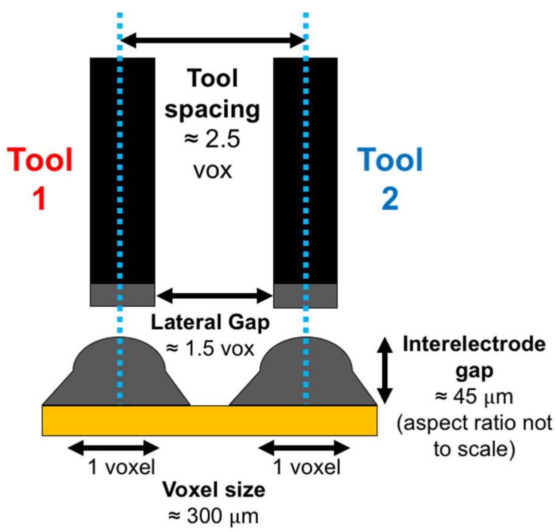


Figure 1. Schematic of the multi-electrode head

2.2. Structure design and parameters

The characteristic geometry explored in this study was an interdigitated comb structure. Relevant parameters in the design of an interdigital sensor, which determine its capacitance, include the interdigital distance d, number of electrode fingers n, finger width w, and finger width to interdigital distance ratio $r = w/d$. The parameters used in this demonstration are listed in Table 1.

Table 1. Parameters of interdigitated comb structure

Parameter	Symbol	Value
Interdigital distance	d	2.5 voxels (450 µm)
Finger width	w	1.5 voxels (300 µm)
Number of electrode fingers	n	5
Digit width to distance ratio	r	2:3

The comb structure was divided into separate “spine” and “digit” regions, as shown in Figure 2. To achieve a regular interdigital spacing, a repeating build pattern consisting of five passes with characteristic electrode activation patterns was devised, as detailed in Figure 3.

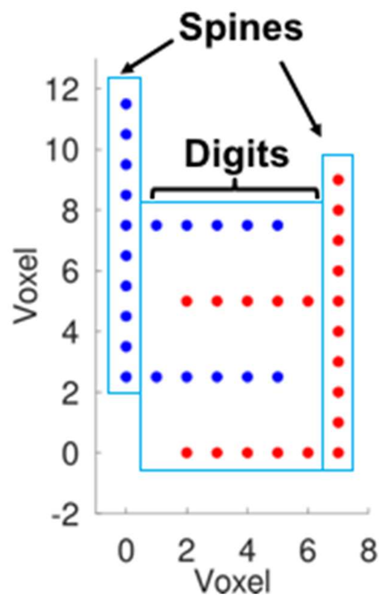
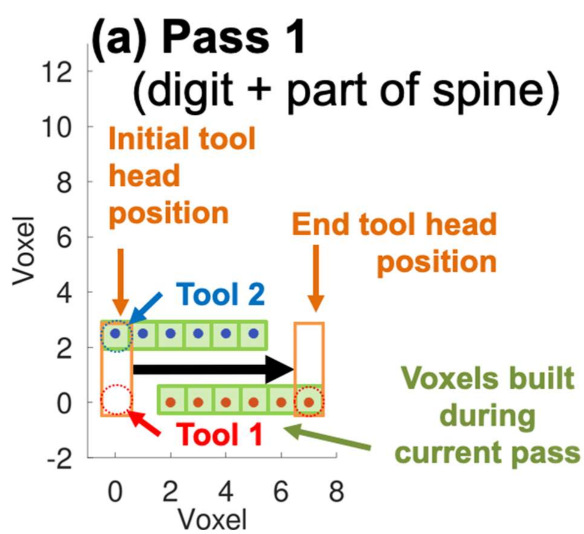
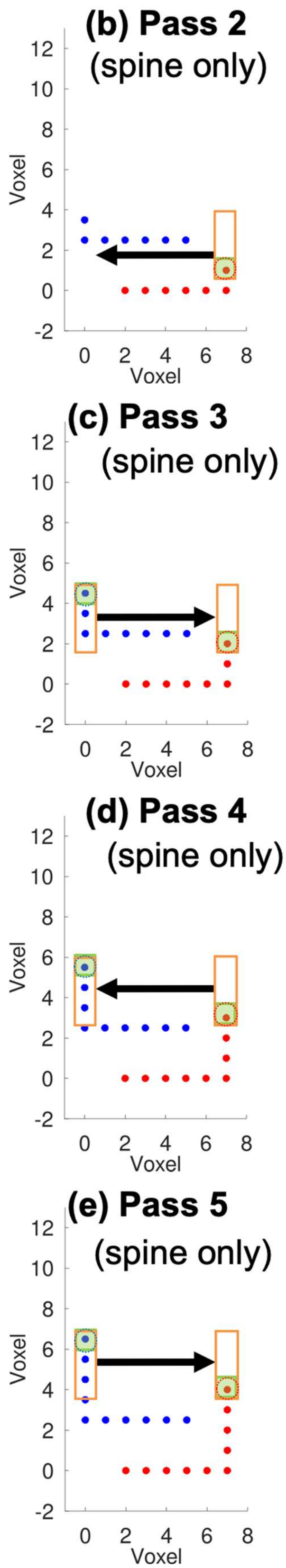


Figure 2. Separation of the comb structure into spine and digit regions





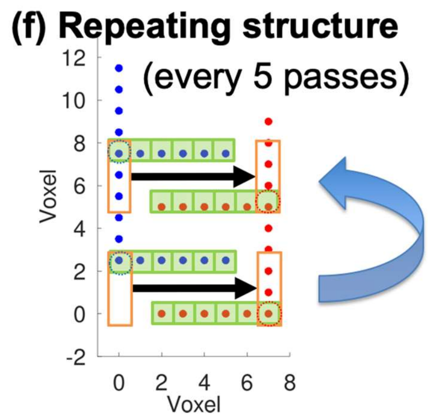


Figure 3. Electrode activation and pass patterns used to build interdigitated comb structure

2.3. Electrochemical setup and feedback system

Electrochemical additive manufacturing was performed using a closed-loop control setup is shown in Figure 4.

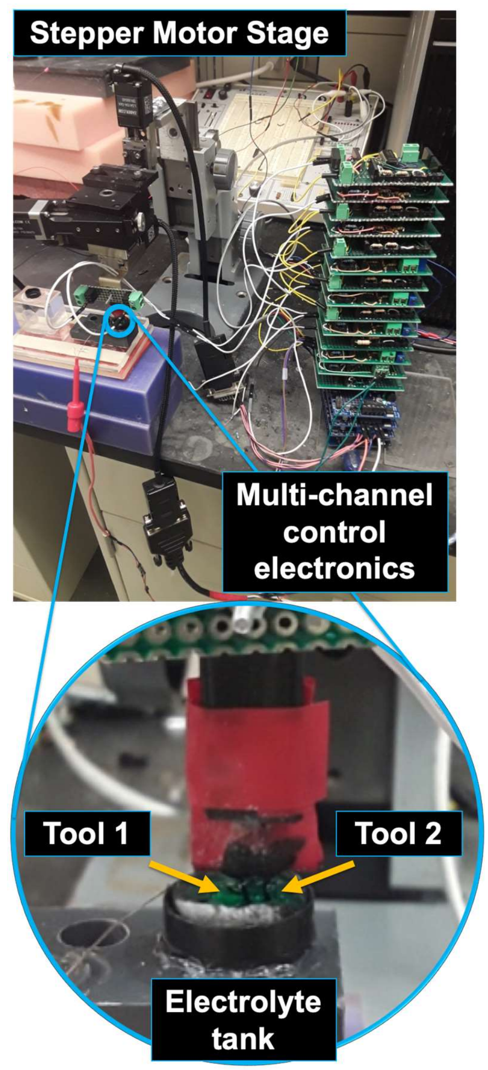


Figure 4. Multi-electrode ECAM setup

This system has the capability to use multiple electrode channels. Instead of individual voxels printed in series, voxels were printed in a parallel manner. At each tool head position, the presence or absence of a voxel was accounted for, and closed-loop deposition was performed if the voxel beneath the given tool was set to be active. The electrolyte used consisted of an aqueous solution of .9 M $NiSO_4 \cdot 6H_2O$, .485 M H_3BO_3, .01 M NaCl, and .00018 M H_2SO_4.

2.4. Trials

Two trials were run using identical geometry. Trial 1 was run using purely closed-loop control. However, some of the voxels farther along the build were observed to have relatively long build times. The use of a time limit was therefore explored in Trial 2. This second trial was run using an initial closed-loop control, with the exception that the system would move to the next parallel voxel if a time limit of 10 minutes was reached.

3. Results and Discussion

The output parts were imaged using a scanning electron microscope; images are respectively shown in Figure 5(a) and (b) for Trials 1 and 2.

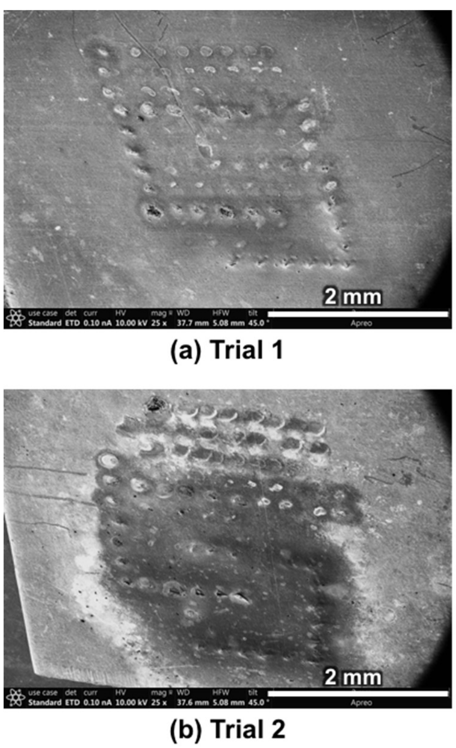


Figure 5. SEM images of deposited interdigitated parts

It can be qualitatively seen that the first trial yielded a shape of closer integrity to the desired one, while the second trial shows more deviation. Both trials show slight marks on the substrate. These are expected artifacts of dual active tool approach; however, the contrast between the intended deposition and the approach marks is significantly stronger in Trial 1, while both are increasingly difficult to distinguish in Trial 2. The weaker-looking deposition is likely due to the shorter build times enforced by the time limit input in trial 2. It is also noted that the output shape becomes less prominent further in the part build across both trials. This was hypothesized to occur due to significant ion depletion with the use of multiple tools, likely requiring a more ion replenishment process.

4. Conclusions

In this study, the feasibility of the deposition of interdigitated electrode structures, a common structure seen across many engineering applications, was demonstrated using a multi-electrode electrochemical additive manufacturing setup. A tool path and electrode activation sequence was devised in order to deposit the desired part from a two-electrode head using multi-channel control circuitry. It was found that a purely closed-loop control operation with no time limit yielded a deposit with qualitatively better geometrical integrity compared to that of deposition with a time limit applied.

Acknowledgments

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