Journal of Power Sources 272 (2014) 356–361

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Laser additive manufacturing of stainless steel micro fuel cells

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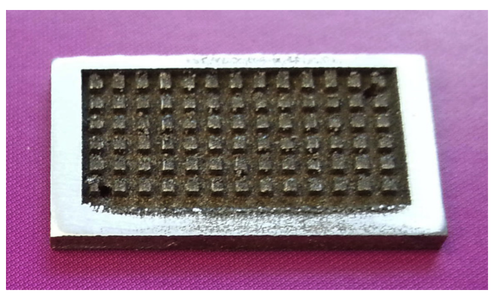
HIGHLIGHTS

- First ever stainless steel micro fuel cells made by laser additive manufacturing.
- Maximum current density: 1.19 A cm^{-2}, maximum power density: 238 mW cm^{-2}.
- The results are comparable to those of macro fuel cells.
- We demonstrated that the method is suitable for fast prototyping.
- The method was used to test flow-field aspect ratio modifications.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 June 2014
Received in revised form
29 July 2014
Accepted 20 August 2014
Available online 2 September 2014

Keywords:
3D printing
Proton exchange membrane
Stainless steel
Fuel cells
Prototyping

ABSTRACT

This paper introduces laser additive manufacturing as a new method for the fabrication of micro fuel cells: The method opens up the capability of ultrafast prototyping, as the whole device can be produced at once, starting from a digital 3D model. In fact, many different devices can be produced at once, which is useful for the comparison of competing designs. The micro fuel cells are made of stainless steel, so they are very robust, thermally and chemically inert and long-lasting. This enables the researcher to perform a large number of experiments on the same cell without physical or chemical degradation. To demonstrate the validity of our method, we have produced three versions of a micro fuel cell with square pillar flowfield. All three have produced high current and power density, with maximum values of 1.2 A cm^{-2} for the current and 238 mW cm^{-2} for power.

1. Introduction

Li-ion secondary cell batteries are the current power source of choice for portable electronics, but micro fuel cells (MFCs) have the potential to further increase energy density [1,2]. MFCs have most commonly been microfabricated from silicon [3–9] but other materials have been utilized, such as metalized PMMA [10–13], SU-8 [14], PDMS [15] [16], pyrolized carbon [17], bulk aluminum [18] and 50 µm thin hydroformed stainless steel sheets [19]. These materials and techniques do not allow for easy disassembly and re-assembly of the cells, and typically, replacing the membrane-electrode assembly (MEA) or the gas diffusion layer (GDL) requires also the replacement of the bipolar plates. Furthermore, few techniques are suitable for fast prototyping: a typical microfabrication process flow requires the preparation of one or more photomasks, the utilization of one or more photolithography steps,

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http://dx.doi.org/10.1016/j.jpowsour.2014.08.096

and processing with separate tools for the etching of the micro-channels and for the deposition of a metallic current collector. While moulding, stamping, and hydroforming are faster methods once the mould, or die is ready, preparation of the mould is, again, a slow process.

Among the established techniques only laser ablation [10,13,20] and CNC machining [11,12] are suitable for rapid prototyping, in the sense that a testable MFC can be produced directly from a design made on a computer, with few processing steps. In our previous work we have optimized the laser ablation parameters for speed [20], disregarding the small irregularities in flow-field channels, as they proved to be inconsequential to the functioning of the MFCs. However, even with the high processing speeds achieved by methods such as laser ablation or CNC machining, the drawbacks of the serial subtractive approach come to the fore when large cavities must be produced. Many MFC designs require the presence of large volume cavities, such as fuel reservoirs [3,4,11], or basins to accommodate thick gas diffusion layers [7,18]. Speeding up CNC machining by using larger milling bits with CNC, or increasing laser ablation speed with larger beam waist and sustained power, is not usually feasible, as these actions would then make it impossible to create sufficiently small microchannels or inlet holes. Finally, it should be mentioned that CNC-milled [11,12] or laser-ablated [10,13] PMMA flow-field plates require a separate metallization step, so that they may collect the produced current.

In this work we introduce laser additive manufacturing (LAM) for the rapid prototyping of stainless steel micro-fuel cells: LAM is a layer-wise material addition technique where complex 3D parts are manufactured by selective melting and solidification of consecutive layers of powder material on top of each other (Fig. 1) [21,22]. LAM can be used both for rapid prototyping as well as for manufacturing of complex metallic objects. The material for our MFCs is 316L stainless steel, a corrosion and acid resistant steel alloy also used for medical implants. Its excellent corrosion resistance combined with its high hardness and toughness permits the experimenter to re-use the MFCs fabricated from it, many times. The electrical resistivity of 316L stainless steel is 74 μΩ cm, which compares favorably to the 10 mΩ cm of highly-doped silicon used in Refs. [7,20]. Because of the low electrical resistivity, the steel flowfield plates are good current collectors.

To assess the viability of LAM for MFC fast prototyping, we have fabricated and tested three variants of a cell with square pillar flowfield and inserted carbon cloth GLD. The difference between the three designs was the size and aspect ratio of the flowfield: 1×1 cm^2, 2×1 cm^2, and 4×1 cm^2. Scaling the flowfield in one dimension is intended to determine if elongated MFCs, suitable for form factors of devices such as mobile phones, would still generate sufficient power and current density compared with 1×1 aspect ratio flowfields.

2. Experimental

2.1. MFC structure and construction

The design of the MFCs in this work is similar to the one in Refs. [7,18]: we have a square pillar flowfield and a basin for accommodating a commercial carbon cloth GDL. An exploded schematic view of the MFC construction is presented on Fig. 2a. All the main feature sizes are summarized on Fig. 2b: the pillars have a 1 mm $\times$ 1 mm cross section, while the channel (inter-pillar distance) is 500 μm wide. There is a 200 μm gap from the top of the pillars to the edge of the flowfield plate. This is done in order to accommodate a commercial carbon cloth GDL. The GDL used was GDL-CT® (Fuel Cell Etc), with the microporous side turned towards the MEA. The GDL was 410 μm thick when not compressed. The MEA was a Gore® Primea membrane (a proton-conductive ionomer similar to Nafion®) with a platinum loading of 0.1 mg cm^{-2} on the anode and 0.3 mg cm^{-2} on the cathode side. Thread seal Teflon® tape (also known as plumber's tape) was stretched on the edge of the flowfield plates, to act as a simple gasket. The MFC was mounted in a matching jig made of ABS polymer by 3D printing.

Fig. 3 shows the 3D models of the three MFC flowfield plates fabricated by LAM. These plates differ only by the flowfield size in one dimension. The flowfield sizes are (a) 1 cm $\times$ 1 cm, (b) 2 cm $\times$ 1 cm, and (c) 4 cm $\times$ 1 cm. The MFCs made with these plates will from now on be called "1×1", "2×1", and "4×1", for convenience.

2.2. LAM of flowfield plates

Fig. 1 presents the process cycle of LAM. In this process, we first create a digital 3D model of the object to be manufactured. This 3D

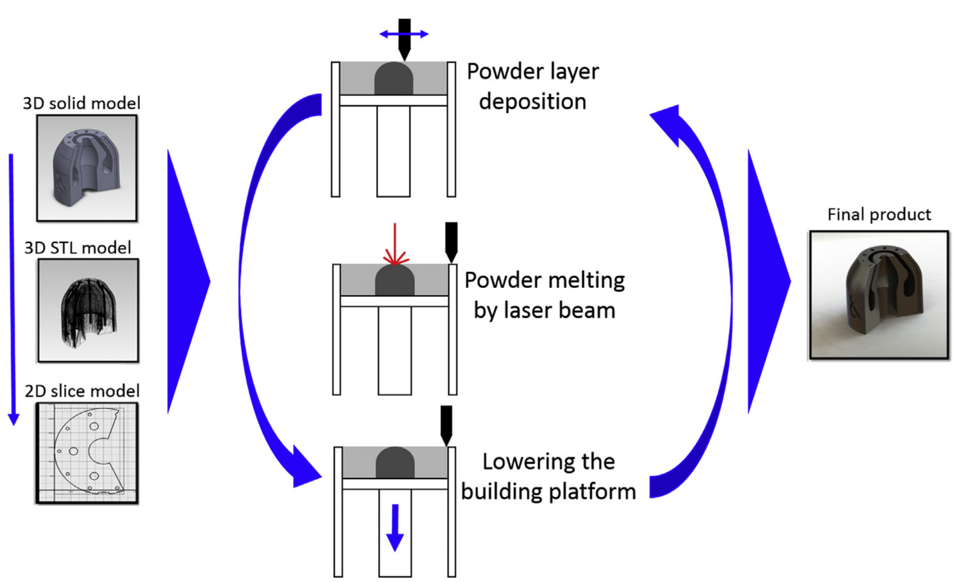

Fig. 1. Diagram of the laser additive manufacturing (LAM) process. On the left: file manipulation from 3D solid model to 3D STL model and to 2D slices. Center: basic principle of laser additive manufacturing process. First the powder is spread then the laser beam melts the geometry of one layer. Finally, then building platform is lowered. The powder is then spread again, and the cycles repeat until the part is finished.