

## Full Length Article

## Copper vertical micro dendrite fin arrays and their superior boiling heat transfer capability



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## ARTICLE INFO

## Article history:

Received 23 February 2017

Received in revised form 20 May 2017

Accepted 29 May 2017

Available online 30 May 2017

## Keywords:

Micro dendrite arrays

Vertical dendrites

Heat transfer

Copper

Multiscale

## ABSTRACT

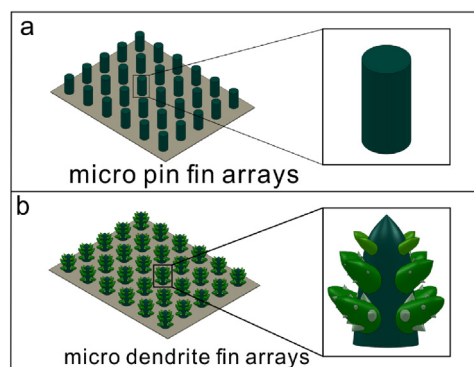
Micro pin fin arrays have been widely used in electronic cooling, micro reactors, catalyst support, and wettability modification and so on, and a facile way to produce better micro pin fin arrays is demanded. Herein, a simple electrochemical method has been developed to fabricate copper vertical micro dendrite fin arrays (Cu-VMDFAs) with controllable shapes, number density and height. High copper sulphate concentration is one key point to make the dendrite stand vertically. Besides, the applied current should rise at an appropriate rate to ensure the copper dendrite can grow vertically on its own. The Cu-VMDFAs can significantly enhance the heat transfer coefficient by approximately twice compared to the plain copper surface. The Cu-VMDFAs may be widely used in boiling heat transfer areas such as nuclear power plants, electronic cooling, heat exchangers, and so on.

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## 1. Introduction

Thanks to the superior capability of heat and mass transfer, micro pin fin array (or the micro pillar array shown in Scheme 1a) has been widely used in the chemical engineering field, e.g. micro reactors [1,2], catalyst support [3], heat transfer enhancement [4–12]. For example, Mei et al. [1] manufactured a micro pin fin array structure on a micro reactor which has been used in hydrogen production by methanol steam reforming. Cao et al. [13] fabricated ZnO/CuO on a silicon micro-pillar array to get a rough super-hydrophobic surface. Thai et al. [14] modified high aspect-ratio micro-pillars by reduction of graphene oxide which has improved the sensor to have a faster response and a greater sensitivity to the detection of NH<sub>3</sub>. Both Rahman et al. [10] and Dhillon et al. [11] found that nanostructured micro pin fins can also effectively increase the critical heat flux by enhancing the liquid supplement due to the capillary performance of the nanostructure.

These micro pin fin arrays are often manufactured using the micro machining technique [12] and the MEMS fabrication technique [4]. But both of these techniques are based on complicated mechanical machine tools and have a long process flow. So devel-



**Scheme 1.** Schematic illustration of (a) micro pin fins arrays; (b) micro dendrite fin arrays.

oping a simple and efficient method to produce micro pin fin arrays must be very promising.

As we know, metal dendrites are natural multi-scale structures because of their branching structure which often boasts primary branches, secondary branches and even tertiary branches and they can be easily fabricated electrochemically [15–19]. So they can be used as a multi-scale micro pin fin, if the metal dendrites can stand vertically, as shown in Scheme 1b). Unfortunately, most dendrites lie down easily during fabrication. Only vertical Co [20], Ni [21]

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dendrites have been reported previously. To the best of our knowledge, there is no publication concerning copper vertical dendrites, which have higher electronic conductivity and higher thermal conductivity than any other metals except Ag. So developing a simple electro-deposition way of manufacturing vertical copper dendrite arrays could be a possible way to produce copper multi-scale micro pin fin arrays.

Herein, an easy electrochemical method has been reported to prepare copper vertical micro dendrite fin arrays (Cu-VM DFA). In this method, an increasing linear current is applied and the number density, length and size of the copper dendrite are controlled by deposition conditions, such as the rising rate of current, the sulfuric acid concentration, and deposition time. Finally, the Cu-VM DFA is applied to enhance boiling heat transfer after sintering in a reducing atmosphere.

## 2. Experimental section

### 2.1. Sample preparation

Cu-VM DFAs were deposited on the copper surface by applying an increasing linear current which started at 0.3 A. Before reaction, high-purity copper plates whose reaction area is 3 cm<sup>2</sup> were cleaned with dilute sulfuric acid, hot dilute caustic solution, and deionized water, and were then used as the substrate (cathode), and counter electrode (anode) which was about 4 times larger than the cathode. The distance between the two electrodes was kept at 3.5 cm and the dendrite growth progress was performed in stationary solution in which the CuSO<sub>4</sub> concentration was kept constant at 0.6 M at room temperature. After reaction, the cathode was covered

with micro copper dendrite array next it was rinsed with deionized water and then dried using a hairdryer.

### 2.2. Pool boiling test

The pool boiling test has been used to investigate the heat transfer performance of the Cu-VM DFA surface. The test sample was a copper cylinder with a diameter of 19 mm and thickness of 5 mm. The top surface of the test sample was fabricated using Cu-VM DFA. Fig. S1 shows the pool boiling experimental set-up. Copper block with 6 ceramic rod heaters inside was used as the heat source. The test sample was welded to the copper block to decrease the thermal resistance between the sample and the copper block. An Aerogel blanket was used to decrease the heat leak to the environment. Two T-type thermocouples with an accuracy of 0.3 °C were connected to the data acquisition unit (Agilent 34970A). One was 3.5 mm below the Cu-VM DFA surface, and the other was located in the boiling vessel. Ultra-pure water was used as the working fluid after boiling for 30 min. The reliability of the present experiment set-up was tested using a plain copper surface, the error of whose pool boiling curve was within +10% compared to the Rohsenow model [22].

## 3. Results and discussion

### 3.1. Cu-VM DFA preparation

A typical Cu-VM DFA (Sample A) was characterized by scanning electron microscopy (SEM, JSM 6510), and the top view and tilt view of Cu-VM DFA is shown in Fig. 1. It indicates that the copper den-

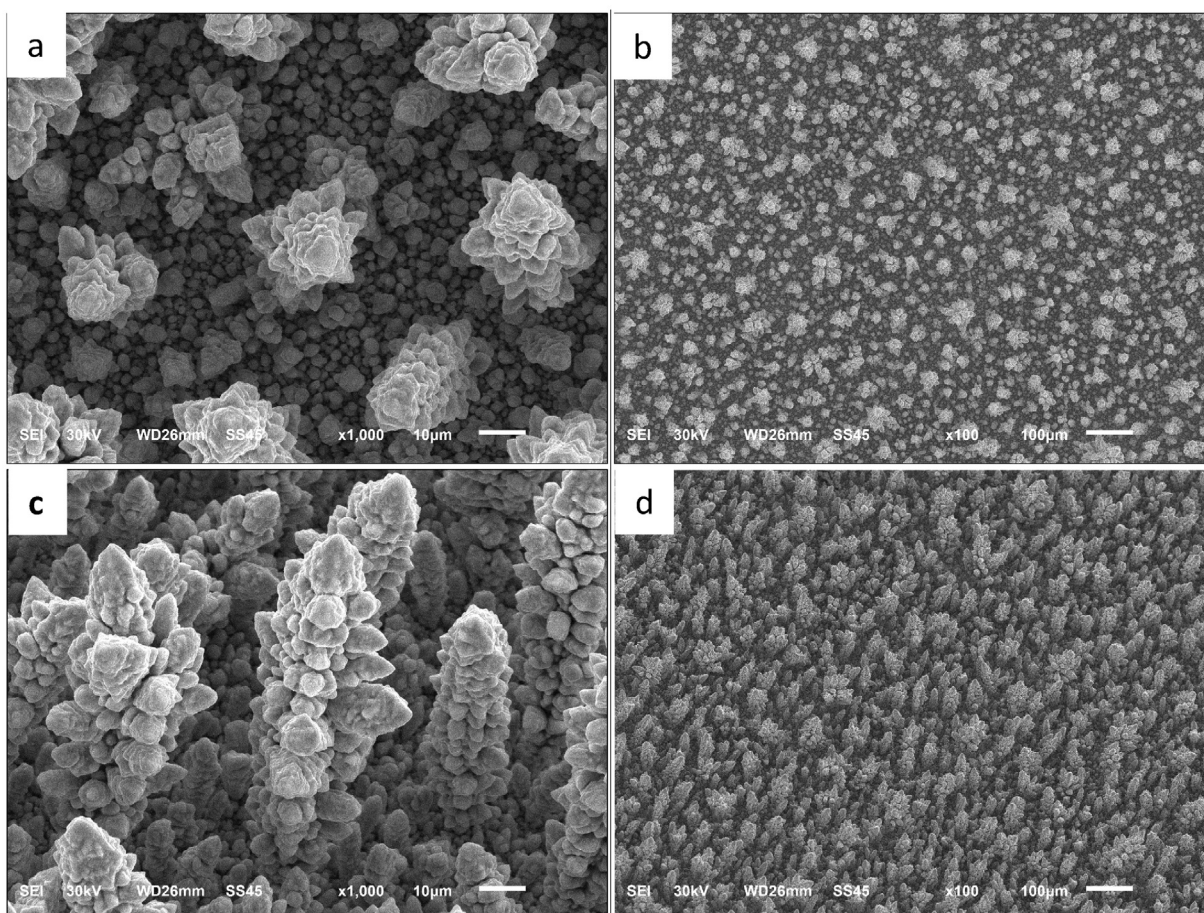


Fig. 1. Typical Cu-VM DFA (Sample A) fabricated with current increasing from 0.1 A/cm<sup>2</sup> to 0.3 A/cm<sup>2</sup> linearly in 300 s (a) (b) top view (c) (d) tilt view (40°).

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