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A novel in-situ nanostructure forming route and its application in pool-boiling enhancement

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ABSTRACT

Dealloying has been recognized as an effective way to fabricate metallic nanoporous structure. In this experimental study, a novel in-situ nanostructure forming route is proposed, which combines surface alloying and dealloying processes. By controlling the in-situ reaction–diffusion process of surface alloying and the in-situ nano-porosity forming process of dealloying, 3-D well ordered nanoporous copper surface (NPCS) was obtained. The NPCS shows significant enhancement in heat transfer coefficient and reduction in wall superheat compared with those of flat surface in visualization designed pool boiling experiments, which can be attributed to the higher active nucleation site and the improvement in wettability on nanoporous surface. The NPCS presents good stability in chemical composition and 3D nanoporous structure, which indicates a promising prospect for long-term application.

1. Introduction

Boiling heat transfer can provide tremendous heat transfer coefficient under a low superheat condition due to the latent heat of working fluid during phase transition process, which is recognized as an effective way for cooling high power devices. It is widely accepted that surface structures play a crucial role in the enhancement of pool boiling heat transfer [1–4]. With the development of nanotechnology, it is possible to manufacture various nanostructures on metallic solid surface, such as nanoparticle, nanotube, nanofilm, and nanoporous structure. Different kinds of nanostructures have been used in enhancing heat transfer studies, and these structures showed dramatic enhancement of heat transfer [5–9]. Patil et al. [10] reported that a significant enhancement in heat transfer coefficient of 17.9 W/cm^2 K was obtained from a copper chip with cauliflower-like morphology fabricated by a two-step electrodeposition process. Lee et al. [11] discussed boiling heat transfer performance of a nano-coated surface which is fabricated by anodizing technology. They found a lower wall superheat at the onset of nucleate boiling and a higher nucleate boiling heat transfer coefficient than that of the plat surface. Ji et al. [12] investigated the critical heat flux (CHF) of a 3-D porous coating surface formed by sintered particles, and got 3.7 times of that of the plain surface. Xu et al. [13] fabricated a composite copper porous surface by electrochemical deposition. Experimental results revealed that the heat transfer coefficient of the porous surface is high up to 5.9 W/cm^2 K, 120% higher than that of the plain surface. Tang et al. [14] adopted a method of hot-dip galvanizing/dealloying to fabricate a nanoporous structure on copper surface, and found a reduction of 63.3% in wall superheat and an increase of 172.7% in heat transfer coefficient compared with the non-structure in pool boiling experiments. However, among these similar works, it's hard to control the formation process of alloy and the characteristic of nanostructure. Metallic nanoporous structure shows promising prospects for the application in pool boiling heat transfer enhancement due to its excellent advantages, including high specific surface area, high thermal conductivity, excellent mechanical properties, good chemical stability and regulated uniform porosity. Among the available technologies, dealloying has been proved to be a highly productive and controllable route to fabricate nanoporous noble metal with three-dimensional ligament-channel structure at nanometer scale [15].

Up to date, nanoporous copper has been fabricated by dealloying Mn–Cu [16], Al–Cu [17], Mg–Cu [18] and Zn–Cu alloys systems [19]. In this paper, Zn–Cu alloy layer is chosen as the precursor since the high potential difference between Zn and Cu (1.104 V/SHE), which

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means that the dealloying process can be easily manipulated [15]. The alloying method shows a great effect on the homogeneous and isotropic of nanoporous structures. Casting [20], sputtering [21] and rolling [22] were successfully applied in fabricating various dealloying precursors in bulk or film material which are aimed at forming metallic bulk or film nanoporous material. However, the fabrication of metallic nanoporous surface by dealloying has not been well studied.

In this study, a novel in-situ nanostructure forming route combined surface alloying and dealloying processes is proposed for facile fabrication of well-ordered nanoporous copper surface (NPCS). The heat transfer performance and the bubble dynamics on the obtained NPCS are systematically studied by visualization designed pool boiling experiments.

2. Experimental details

2.1. Preparation of nanoporous surface

A novel in-situ nanostructure forming route is schematically shown in Fig. 1. The fabrication process was the combination of surface alloying and dealloying processes. Firstly, some pretreatments were conducted, which include degreasing with 5 wt% NaOH solution, removing the oxide layer on the surface through putting the test parts in 5 wt% hydrochloric acid solution for 5 min, ultrasonic cleaning in deionized water and low temperature drying. Secondly, the electroplating and thermal alloying were employed for fabrication of a Cu–Zn alloy layer. Electroplating is used to stack a zinc alloy layer on the copper substrate. During electroplating process, a simple-two-electrode arrangement was used where copper was served as a cathode, zinc (99.99%) as an anode. A zinc layer was electrodeposited at room temperature (298 K) on the copper substrate in an aqueous solution containing 80 g/L Zn_2Cl, 200 g/L KCl and 35 g/L $3HB_3O$ with PH of about 5 for 10 min at a current density of 1.2 A/dm^2. In the thermal alloying step, heat treatment at 473 K for 2 h was conducted in a vacuum sintering furnace with a protective atmosphere of H_2. Thirdly, the dealloying was accomplished by a free corrosion method at room temperature [23]. The as-alloyed sample was simply immersed in 0.125 M HCl for 48 h, then rinsed by deionized water, finally dried.

2.2. Characterization of nanoporous surface

The NPCS was characterized with a field emission scanning electron microscope (FE-SEM) (LEO 1530VP). And an element analysis of NPCS was also conducted by an energy dispersive spectroscopy (EDS) (Bruker Company, Germany). Fig. 2 shows the FE-SEM image and EDS analysis of NPCS. The NPCS presents uniform porosity with approximately 30–200 nm. Due to different zinc contents, the phase constituents are different for Cu–Zn alloys. With the increase of zinc content, the bi-phase alloy exists in the Cu–Zn alloys, which is easier for dissolving than the single phase alloy in the dealloying process [15]. Therefore, zinc atoms of alloy layer surface and some copper atoms in the form of Cu–Zn compound were dissolved. The final surface morphology is determined by the competition between the curvature dependent dissolutions of zinc and copper [24]. Fig. 2 also shows that the NPCS is mainly consisted of copper, indicating that zinc is removed completely during dealloying.

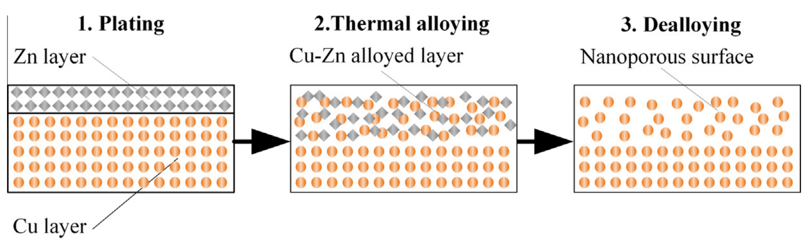

Fig. 1. Schematic of in-situ nanoporous forming route for NPCS.

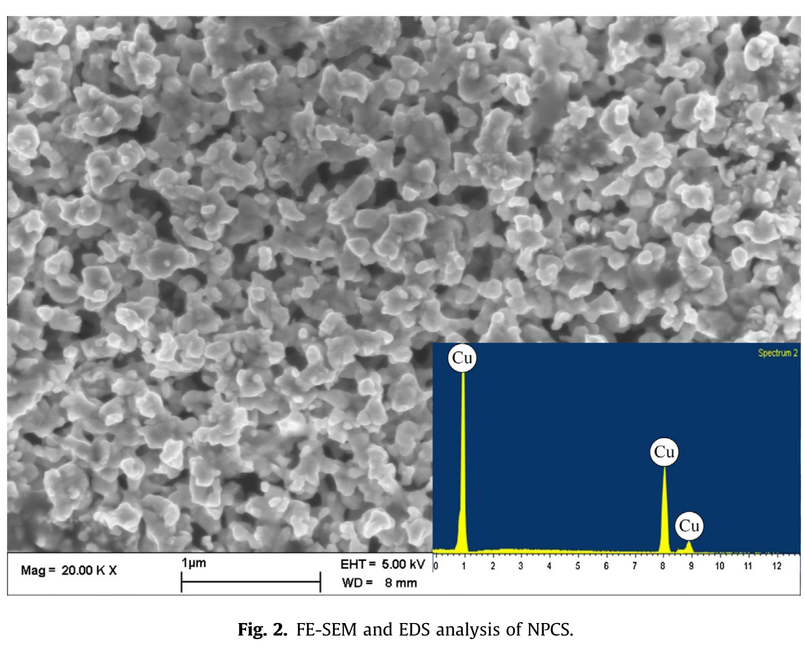

Fig. 2. FE-SEM and EDS analysis of NPCS.