

Experimental Study on Pool Boiling Heat Transfer Enhancement of Micro-Nano Coupled Surfaces Postprint

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Abstract

Using deionized water as the working fluid, micro-grooves were fabricated on titanium plate surfaces by wire-cut electrical discharge machining, and a micro/nano-coupled surface with titanium dioxide nanotube arrays was prepared via anodic oxidation to investigate its enhanced boiling heat transfer performance. The microstructural morphology was characterized by field emission scanning electron microscopy, and the static contact angle of the surface was measured using a contact angle goniometer. The results demonstrate that, compared with a plain surface, the micro-groove structure increases the heat transfer area, the ordered nanotube arrays exhibit hydrophilic characteristics with a significantly reduced contact angle. The heat transfer coefficient and critical heat flux of the micro/nano-coupled surface reach $15.5 \text{ kW} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$ and $420.1 \text{ kW} \cdot \text{m}^{-2}$, respectively, corresponding to enhancements of 158.3% and 50%. Based on experimental observations and mechanistic analysis, the microchannel structure of the micro/nano-coupled surface provides support for continued bubble growth, effectively preventing the heat transfer wall from being completely covered by coalesced large bubbles; after the superheat reaches a certain temperature, smaller nucleation sites are activated, and the superheat exhibits a decreasing trend with increasing heat flux. The micro/nano-coupled surface demonstrates an enhancement effect on pool boiling.

Full Text

Preamble

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Experimental Study on Enhanced Pool Boiling Heat Transfer on Micro-Nano Coupled Surfaces

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Abstract

Using deionized water as the working fluid, micro-channels were fabricated on titanium plate surfaces by wire-cutting, and TiO₂ nanotube arrays were prepared via anodic oxidation to create micro-nano coupled surfaces. The enhanced boiling heat transfer performance of these surfaces was investigated. Microstructural morphology was characterized by field emission scanning electron microscopy, and static contact angles were measured using a contact angle goniometer. Results show that compared with smooth plates, the micro-channel structure increased the heat transfer surface area, while the regular nanotube arrays exhibited hydrophilic properties with significantly reduced contact angles. The heat transfer coefficient and critical heat flux density of the micro-nano coupled surface reached $15.5 \text{ kW} \cdot \text{m}^{-2} \cdot \text{°C}^{-1}$ and $420.1 \text{ kW} \cdot \text{m}^{-2}$, respectively, representing improvements of 158.3% and 50%. Combined experimental observations and mechanism analysis reveal that the microchannel structure of the micro-nano coupled surface provided support for continued bubble growth, effectively preventing the heat transfer wall from being completely covered by merged large bubbles. After the superheat reached a certain temperature, smaller activation sites were activated, causing the superheat to decrease as heat flux density increased. The micro-nano coupled surface demonstrates significant enhancement of pool boiling heat transfer.

Keywords: micro-nano coupling; pool boiling; heat transfer; TiO₂ nanotube arrays

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0 Introduction

Enhanced boiling heat transfer holds significant importance in industrial applications. Researchers have substantially improved boiling heat transfer performance through micro-machining of boiling surfaces using mechanical processing methods and metal sintering techniques.

Demir et al. [1] investigated three silicon nanorod structures with dimensions of 900, 1800, and 3200 nm, achieving a 254% enhancement compared to silicon flat plates. Yu et al. [2] fabricated rectangular arrays of different sizes on copper substrates, increasing the critical heat flux (CHF) by five times compared to flat plates. Das et al. [3] processed parallel or crossed channels on copper columns with annular grooves, rectangular, and circular treatments at channel ends, resulting in varying degrees of enhancement in both CHF and heat transfer coefficient (HTC). Kim et al. [4] demonstrated that microstructures can effectively improve boiling heat transfer and CHF, with HTC increasing by 300% and CHF by 350%. Mostafa et al. [5] summarized recent applications

of micro-nano porous structures in pool boiling experiments, all showing improvements in HTC and CHF. Jun et al. [6] prepared microporous coatings on copper surfaces, achieving a maximum HTC of $400 \text{ kW/m}^2 \cdot \text{K}$ and CHF of 2.1 MW/m^2 . Das et al. [7] deposited silicon dioxide nanocoatings on metal surfaces using electron beam vapor deposition, reducing superheat by 36% and increasing HTC by 58%. Sarangi et al. [8] fabricated copper particle layers on heated copper surfaces using free particle technology, with wall superheat significantly lower than sintered coatings. Pratik et al. [9] used chemical vapor deposition on silicon substrates with foam-like h-BN (hexagonal boron nitride) as a bonding layer, achieving improvements in both HTC and CHF while reducing superheat by 30%. Xu et al. [10] prepared composite micro-nano porous surfaces through electrodeposition sintering, which exhibited high CHF values reaching 239 W/cm^2 . Fan et al. [11] investigated the effect of sintered porous tubes on falling film evaporation heat transfer, finding that the internal falling film heat transfer coefficient of porous tubes was 2.03 times that of smooth tubes, with overall heat transfer coefficient 1.78 times higher.

Researchers have also found that combining channel microgrooves with nanoporous coatings can substantially improve enhancement effects. Arvind et al. [12] prepared three channel widths of 300 μm , 500 μm , and 762 μm , then sintered nano-coatings, achieving CHF of 420 W/cm^2 and heat transfer coefficient of $2.9 \text{ MW/m}^2 \cdot \text{K}$. Deng et al. [13] fabricated porous structures on X-shaped grooves and annular cavities using solid-state sintered copper powder, conducting pool boiling experiments with deionized water and ethanol as working fluids. The porous structures significantly reduced superheat, improved HTC, enhanced liquid wettability, and prevented heat transfer deterioration. Patil et al. [14] prepared microporous coatings on fin-type microchannels using electrodeposition, achieving CHF of 3250 kW/m^2 and HTC of $995 \text{ kW/m}^2 \cdot \text{K}$.

Based on titanium plates, this study mechanically fabricated micro-scale groove structures and employed anodic oxidation to prepare TiO₂ nanotube array surfaces. Using deionized water as the working fluid, the enhanced heat transfer characteristics of micro-nano coupled surfaces were investigated.

1 Experimental Design

1.1 Experimental Apparatus

The experimental apparatus is shown in Figure 1 [Figure 1: see original paper] and consists of three components: heat source, data acquisition, and image capture. The heat source is an electric heating rod with a maximum power output of 600 W. The image capture system comprises a high-speed camera (PCO 1200hs) and an LED light source. The data acquisition unit includes a data logger (KEYSIGHT 34972A) and five PT100 thermal resistors with an accuracy of $\pm 0.05^\circ\text{C}$, positioned as shown in Figure 2 [Figure 2: see original paper] (at locations T1, T2, T3).

1.2 Preparation and Characterization of Micro-Nano Coupled Surfaces

Using 50×50×2 mm titanium plates with 99.9% purity as substrates, micro-channel structures were fabricated by wire-cutting technology, as shown in Figure 3 [Figure 3: see original paper]. The micro-channel dimensions were 400 μm groove depth, 762 μm groove width, and 200 μm rib width. After wire-cutting, an anodic oxidation process [15] was employed to prepare nanotube porous surfaces. Microstructural morphology was characterized using field emission scanning electron microscopy (Nova Nano SEM450, FEI Company, USA), and static contact angles were measured using an optical contact angle goniometer (DAS30, KRUSS, Germany).

Following anodic oxidation, a nanotube array structure was formed with pore sizes distributed between 150-200 nm, as shown in Figure 4 [Figure 4: see original paper]. Using deionized water as the test solution, the static contact angle of the smooth plate surface was measured at 45.2°, while the nanotube porous surface exhibited a static contact angle of 27.3°, demonstrating hydrophilic properties, as shown in Figure 5 [Figure 5: see original paper].

1.3 Data Processing

Analysis of temperature measurements at three points on the copper column indicates that the heat transfer satisfies one-dimensional conduction, with fitted data showing R² values above 0.99, as illustrated in Figure 6 [Figure 6: see original paper].

The heat flux density in the experiment can be expressed as:

$$q'' = \frac{UI}{L^2}$$

where U and I are the voltage across and current through the copper column, respectively, and L is the side length of the square upper surface of the copper column. According to Fourier's law of heat conduction, the temperature of the heat transfer surface (the temperature at the rib surface) can be calculated as:

$$T_w = T_1 - q'' \left(\frac{L_1}{\lambda_{Cu}} + \frac{L_2}{\lambda_{LM}} + \frac{L_3}{\lambda_{Ti}} \right)$$

where λ_{Cu} , λ_{LM} , and λ_{Ti} are the thermal conductivities of pure copper, liquid metal, and titanium plate, respectively. T_1 is the temperature measured by the uppermost thermal resistor, and L_1 , L_2 , L_3 represent the distance from the centerline of the uppermost thermal resistor to the upper surface of the copper column, the thickness of liquid metal, and the thickness of the heat transfer wall, respectively.

The surface superheat ΔT_w can then be obtained as:

$$\Delta T_w = T_w - T_{sat}$$

where T_{sat} is the liquid temperature inside the container. The heat transfer coefficient h is calculated as:

$$h = \frac{q''}{\Delta T_w}$$

Heat loss was estimated by comparing the total heat input to the device over a period with the latent heat of vaporization required for the measured condensate mass at the outlet. The entire experimental setup was insulated with thermal cotton to minimize heat loss. Calculations indicated that heat loss remained below 5%.

1.4 Uncertainty Analysis

The experimental uncertainty primarily considers measurement errors. Table 1 lists the measurement parameters and their uncertainties.

The uncertainty propagation relationship is as follows:

$$\frac{\Delta q''}{q''} = \sqrt{\left(\frac{\Delta U}{U}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}$$

$$\frac{\Delta h}{h} = \sqrt{\left(\frac{\Delta q''}{q''}\right)^2 + \left(\frac{\Delta T_w}{T_w}\right)^2}$$

Repeatability experiments were conducted on the smooth plate to verify experimental reliability. The maximum error did not exceed 5%, and as shown in Figure 7 [Figure 7: see original paper], data from two experimental runs essentially overlapped, confirming the reliability of the experimental results.

2 Experimental Phenomena and Results Analysis

2.1 Heat Transfer Performance Testing

Pool boiling experiments were conducted on surfaces with different treatments, with boiling curves shown in Figure 8 [Figure 8: see original paper]. The untreated smooth plate exhibited HTC and CHF values of $6 \text{ kW} \cdot \text{m}^{-2} \cdot \text{°C}^{-1}$ and $280 \text{ kW} \cdot \text{m}^{-2}$ (point a), respectively. All modified surfaces showed improvements. The micro-groove surface achieved HTC and CHF of $10 \text{ kW} \cdot \text{m}^{-2} \cdot \text{°C}^{-1}$ and $370 \text{ kW} \cdot \text{m}^{-2}$ (point b), representing 60% and 17.8% improvements over the smooth plate. The nano-porous surface reached HTC and CHF of $10 \text{ kW} \cdot \text{m}^{-2} \cdot \text{°C}^{-1}$ and $330 \text{ kW} \cdot \text{m}^{-2}$ (point c), showing 67% and 17.8% enhancements. The micro-nano coupled surface demonstrated the best performance with HTC and CHF of $15.5 \text{ kW} \cdot \text{m}^{-2} \cdot \text{°C}^{-1}$ and $420.1 \text{ kW} \cdot \text{m}^{-2}$ (point d), corresponding to improvements of 158% and 50%.

At the same heat flux density, the micro-groove, nano-porous, and micro-nano coupled surfaces showed significantly reduced superheat, as illustrated in Figure

9 [Figure 9: see original paper]. At a heat flux of $200 \text{ kW} \cdot \text{m}^{-2}$, the smooth plate exhibited a superheat of 46°C (point a), while the other surfaces showed 34°C (point b), 32°C (point c), and 24°C (point d), respectively. Notably, the wall superheat did not increase monotonically with heat flux but instead showed a decreasing trend at higher heat fluxes, manifesting as a “backward bending” phenomenon in the curve. This behavior was also observed in experiments by Wang et al. [16]. The primary cause may be attributed to the pore size distribution of 150-200 nm in the nano-porous structure. At low superheat, only larger pores formed vaporization nuclei, but when wall superheat exceeded a certain threshold, smaller activation sites became active, causing superheat to decrease with increasing heat flux.

2.2 Bubble Behavior on Micro-Nano Coupled Surfaces

The number and behavior of bubbles during boiling directly correlate with heat transfer performance. Figure 10 [Figure 10: see original paper] shows the boiling conditions on the micro-nano coupled surface at different heat fluxes. Bubbles began to form at $q'' = 175 \text{ kW} \cdot \text{m}^{-2}$ (a). As heat flux increased, the number of effective nucleation sites gradually increased. At $q'' < 264 \text{ kW} \cdot \text{m}^{-2}$ (c), bubbles primarily generated on the ribs of the heat transfer surface, with minimal bubble formation at the bottom of microchannels. This occurred because the rib temperature exceeded that at the channel bottom, resulting in higher local superheat and leaving nucleation sites at the bottom inactive. At $q'' = 285 \text{ kW} \cdot \text{m}^{-2}$ (d), bubbles began generating inside microchannels, and intense coalescence intensified turbulence within the channels, causing more undeveloped bubbles to detach from the channel bottom.

After coalescence in the microchannels, bubbles did not immediately detach but continued growing along the rib sides until reaching critical size. The microchannel bottom remained partially active with small bubbles, preventing complete coverage by large merged bubbles. This mechanism likely explains the effective CHF enhancement of the micro-nano coupled surface. As heat flux further increased, bubble coalescence became more severe, and departure diameters increased until the heat transfer surface was completely covered by a large vapor film, reaching the critical heat flux condition.

3 Conclusions

This study employed mechanical processing and electrochemical methods to prepare micro-nano coupled surfaces on titanium plates. The enhanced heat transfer characteristics were investigated, yielding the following conclusions:

1. Micro-groove, nano-porous, and micro-nano coupled surfaces all reduced wall superheat and improved HTC and CHF. The micro-nano coupled surface achieved HTC and CHF of $15.5 \text{ kW} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$ and $420.1 \text{ kW} \cdot \text{m}^{-2}$, respectively, representing improvements of 158.3% and 50% compared to the smooth surface, demonstrating superior performance.

2. Due to the pore size scale range of the nano-porous surface, larger pores formed activation nuclei at low wall superheat. When wall superheat reached a certain temperature, smaller activation sites became active, causing superheat to decrease with increasing heat flux density and producing a “backward bending” phenomenon in the boiling curve.
3. The nano-porous surface generated more effective vaporization nuclei, while the microchannel structure provided support for continued bubble growth, preventing complete coverage of the heat transfer surface by merged large bubbles and effectively improving CHF.

References

- [1] Demir E, Izci T, Alagoz A S, et al. Effect of Silicon Nanorod Length on Horizontal Nanostructured Plates in Pool Boiling Heat Transfer with Water [J]. *International Journal of Thermal Sciences*, 2014, 82(8): 111-121
- [2] Yu C K, Lu D C. Pool Boiling Heat Transfer on Horizontal Rectangular Fin Array in Saturated FC-72[J]. *International Journal of Heat and Mass Transfer*, 2007, 50(17-18): 3485-3492
- [3] Das A K, Das P K, Saha P. Performance of Different Structured Surfaces in Nucleate Pool Boiling[J]. *Applied Thermal Engineering*, 2009, 29(17): 3643-3653
- [4] Kim S H, Lee G C, Kang J Y, et al. Boiling Heat Transfer and Critical Heat Flux Evaluation of the Pool Boiling on Micro Structured Surface[J]. *International Journal of Heat and Mass Transfer*, 2015, 91(12): 1140-1147
- [5] Shojaeian M, Koşar A. Pool Boiling and Flow Boiling on Micro-and-Nanostructured Surfaces [J]. *Experimental Thermal and Fluid Science*, 2015, 63(5): 45-73
- [6] Jun S, Kim J, Son D, et al. Enhancement of Pool Boiling Heat Transfer in Water Using Sintered Copper Microporous Coatings [J]. *Nuclear Engineering and Technology*, 2016, 48(4): 932-940
- [7] Das S, Kumar D S, Bhaumik S. Experimental Study of Nucleate Pool Boiling Heat Transfer of Water on Silicon Oxide Nanoparticle Coated Copper Heating Surface [J]. *Applied Thermal Engineering*, 2016, 96(3): 555-567
- [8] Sarangi S, Weibel J A, Garimella S V. Effect of Particle Size on Surface-Coating Enhancement of Pool Boiling Heat Transfer[J]. *International Journal of Heat and Mass Transfer*, 2015, 81(2): 103-113
- [9] Pratik KC, Abdullah N, Ashton T S, et al. Saturated Pool Boiling Heat Transfer from Vertically Oriented Silicon Surfaces Modified with Foam-like Hexagonal Boron Nitride Nanomaterials [J]. *International Journal of Heat and Mass Transfer*, 2016, 95(4): 964-971

- [10] Xu Pengfei, Li Qiang, Xuan Yimin. Enhanced Boiling Heat Transfer on Composite Porous Surface International Journal of Heat and Mass Transfer, 2015, 80(1): 107-114
- [11] Fan Yongjian, Xu Hong, Xu Peng. Heat Transfer Experiment of Falling-Film Evaporation in Vertical Porous Tube [J]. CIESC Journal. 2016, 67(2): 512-518
- [12] Jaikumar A, Kandlikar S G. Ultra-High Pool Boiling Performance and Effect of Channel Width with Selectively Coated Open Microchannels[J]. International Journal of Heat and Mass Transfer, 2016, 95(4): 795-805
- [13] Deng Daxiang, Feng Junyuan, Huang Qingsong, et al. Pool Boiling Heat Transfer of Porous Structures with Reentrant Cavities[J]. International Journal of Heat and Mass Transfer, 2016, 99(8): 556-568
- [14] Patil C M, Kandlikar S G. Pool Boiling Enhancement through Microporous Coatings Selectively Electrodeposited on Fin Tops of Open Microchannels [J]. International Journal of Heat and Mass Transfer, 2014,79(12): 816-828
- [15] Wang Xinliang. The Experimental Research of Boiling Heat Transfer with TiO Nanotube Array Surface Titanium [D]. Tianjin: Hebei University of Technology, 2013
- [16] Wang Yaqiao, Mo Dongchuan, Lv Shushen. Effects of Copper Micro-Nano Bi-Porous Surface Thickness on Boiling [J]. Journal of Engineering Thermal-physics, 2016, 37(7): 1519-1522

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