Research Article

Antibacterial Characteristics of Lotus-Type Porous Copper

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Lotus-type porous copper with long cylindrical pores aligned parallel to the solidification direction was studied for use as an antibacterial material. The antibacterial performance of lotus-type porous copper samples with different specific surface areas against *Escherichia coli* was investigated. The results confirmed that the antibacterial effect gradually increased with specific surface area. The correlation between the pore structure of lotus-type porous metals and their antibacterial effect was also analyzed in detail. Our research proposes a new application of these metals in the water purifying system.

1. Introduction

In addition to offering convenience and many lifestyle options, industrial development has caused serious environmental contamination, especially water pollution, which increases the growth of various bacteria, viruses, and protozoa that cause water-borne diseases. Removal of disease-causing organisms from drinking water is, therefore, extremely important for human health. There are several conventional chemical disinfectants such as chlorine and its derivatives and ozone [1]. However, many of these agents are carcinogens with potential harmful side effects [2].

In this regard, several researchers have recently investigated the use of inorganic antibacterial materials such as silver and copper to inhibit microbial growth. In particular, research studies on porous antibacterial materials are well under way because the antibacterial effect is proportionate to the increase in surface area [3–5]. Shen et al. [3] evaluated the antibacterial characteristics of porous ceramic composites that were decorated with ultrafine silver (II) oxide particles and fabricated by chemical oxidation. Chen et al. [4] examined Cu-TiO₂ nanocomposites that could be created

by photocatalytic reduction and studied their antibacterial performance in the absence of light.

Lotus-type (or Gasar) porous metals [6, 7], which have long cylindrical pores aligned parallel to the solidification direction, have many advantages over other materials for antibacterial applications. For example, the specific surface area of these metals can be easily controlled by manipulating the porosity and pore diameter [6, 8–10]. These metals also exhibit high fluid permeability because of their low pressure drop [6, 11]. In addition, they are easy to manufacture and are suited for mass production because their fabrication is based on the casting process [6, 8, 10]. However, the antibacterial performance of lotus-type porous metals has not been evaluated.

Here, we show the antibacterial performance of lotus-type porous metals with various specific surface areas that were controlled by hydrogen gas pressure and solidification velocity [6, 8, 10]. Lotus-type porous copper was selected for the antibacterial test because copper has much higher antimicrobial activity than other metals such as silver, aluminum, silicon, and tin [12]. The correlation between pore structure and antibacterial effect will also be discussed in detail.

2. Materials and Methods

2.1. Preparation of Lotus-Type Porous Copper. Lotus-type porous copper ingots with various porosities and pore diameters were fabricated by mold casting [8] and continuous casting [10] according to a previously described procedure. In brief, the fabrication of lotus-type porous copper is a continuous process comprising a series of hydrogen gas pressurization, induction melting, and directional solidification stages. Each ingot was cut into rectangular parallelepipeds ($25 \times 25 \times 2.5 \text{ mm}^3$) by using a spark-erosion wire-cutting machine (A325; Sodick Co., Japan). Nonporous and lotus-type porous copper samples were polished with a series of emery papers, washed in ultrasonic cleaner, and finally dried in hot air. The porosity of each sample was obtained from the following equation:

$$\text{Porosity (\%)} = \left(1 - \frac{\rho}{\rho_0}\right) \times 100, \quad (1)$$

where ρ and ρ_0 are the apparent density of the porous copper and the density of nonporous copper, respectively. The pore diameter was measured in the cross-section perpendicular to the solidification direction by using an image analyzer (Image-Pro Plus; Media Cybernetics Co., USA). The specific surface area was also calculated on the basis of the assumption that the pores were perfectly cylindrical.

2.2. Antibacterial Activity. *Escherichia coli* (*E. coli*; KCTC 2223) used in this study was a strain from the Korean Collection for Type Culture (KCTC, Daejeon, Korea). The nonporous and lotus-type porous copper samples were immersed in 100 mL of phosphate-buffered saline (PBS) solution containing approximately 10^2 cfu/mL *E. coli*, for specific time intervals of 15, 30, 45, 60, 90, and 120 min at room temperature. To obtain the bacterial concentration, the 3 M Petrifilm *E. coli* count plate method was used: 1 mL of the bacterial suspension was dispensed on Petrifilms by using a micropipette; the films were then placed in an incubator at $37 \pm 1^\circ\text{C}$ for 24 h. The antibacterial rate was determined using the following formula [13]:

$$\text{Antibacterial rate (\%)} = \frac{N_1 - N_2}{N_1} \times 100, \quad (2)$$

where N_1 and N_2 are the bacterial count, when using the control material (304 stainless steel) and the nonporous or lotus-type porous copper, respectively. The concentration of copper ions in distilled water was also verified with an inductively coupled plasma mass spectrometer (ICP-MS; ELAN 6100, Perkin-Elmer SCIEX, Canada).

3. Results and Discussion

Figure 1 shows the cross-sectional views perpendicular to the solidification direction of the lotus-type porous copper samples. In addition, the measured porosity, average pore diameter, and specific surface area of the samples are summarized in Table 1. The specific surface area of the lotus-type porous copper samples was much higher than that of

TABLE 1: Porosity, average pore diameter, and specific surface area of nonporous and lotus-type porous copper samples.

	Nonporous copper	Lotus-type porous copper		
		A	B	C
Porosity (%)	—	72.2	71.4	47.8
Average pore diameter (μm)	—	1128.3	670.6	222.1
Specific surface area (cm^2/g)	1.1	6.5	9.0	14.1

nonporous copper, and it depended on the average pore diameter and pore distribution. In particular, the specific surface area of sample C was almost 14 times the value for nonporous copper.

Figure 2(a) shows the antibacterial effect of nonporous and lotus-type porous copper with various specific surface areas as a function of the immersion time. The term “reference” refers to data obtained without involving copper samples. The antibacterial performance of copper gradually increased with increasing specific surface area. Figure 2(b) shows the antibacterial rate calculated using (2). It can be seen that after 30 min of coculturing with *E. coli*, the antibacterial rates of sample C reached $>99.999\%$, showing strong antibacterial functions.

Figure 3 shows the number of dissolved copper ions in distilled water after immersing samples of nonporous and lotus-type porous copper (sample C) for various time intervals. These values were verified by ICP-MS analysis. The number of copper ions from the porous copper sample was much higher than that from the nonporous copper sample; the numbers increased with increasing immersion time.

There are several reasons why lotus-type porous copper showed better antibacterial performance when compared to nonporous or conventional porous copper. First, specific surface area affects antibacterial performance. The antibacterial mechanism of metallic antibacterial materials can be classified by the action of metallic ions and active oxygen generated on the surface [14]. This characterization was expected in our experiment since more *E. coli* were exposed to copper as the samples' specific surface area increased. The morphology of lotus-type porous metals comprised cylindrical pores aligned parallel to the solidification direction. Thus, this configuration yielded large surface areas when the ingots were cut perpendicular to the solidification direction because almost all the pores were open.

Another accelerating factor for the antibacterial performance may be crevice corrosion. Crevice corrosion is a rather aggressive form of corrosion that arises in the narrow gaps between a metal and another material, and it accelerates the elution of metal ions. In general, the corrosion behavior of porous metals is a very serious disadvantage when compared to bulk metals, particularly in case of crevice corrosion. Corrosion is also influenced by the morphology of pores and the specific surface area [15]. However, corrosion may offer a rather significant benefit from a different perspective, especially regarding the antibacterial effect. Although this experiment was conducted in the PBS solution, which has low

FIGURE 1: Cross-sectional views perpendicular to the solidification direction of lotus-type porous copper with various specific surface areas: (a) 6.5 cm²/g; (b) 9.0 cm²/g; (c) 14.1 cm²/g.

FIGURE 2: Time-course study of the (a) population and (b) antibacterial rates of nonporous and lotus-type porous copper against *E. coli*. The term “reference” in (a) refers to data obtained without involving copper samples.

FIGURE 3: Number of dissolved copper ions in distilled water after immersing the nonporous and lotus-type porous copper samples for various time intervals.

chloride ion concentration and buffering capability, lotus-type porous metals have many narrow pores as noted above, and the crevice corrosion effect cannot be overlooked.

4. Conclusions

In this study, the antibacterial performance of lotus-type porous copper was evaluated and the correlation between pore structure and the antibacterial effect was analyzed. The antibacterial performance of lotus-type porous copper gradually increased with increasing specific surface area. This was because the specific surface area and crevice corrosion behavior were influenced by the pore morphology of lotus-type porous metals. Based on our research, we believe lotus-type porous metals have potential applications in the healthcare industry, especially water purifying system.

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