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Effect of silver on microstructure and antibacterial property of 2205 duplex stainless steel

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ABSTRACT

In this study, 2205 duplex stainless steel (DSS) was employed to enhance the antibacterial properties of material through silver doping. The results demonstrated that silver-doped 2205 DSS produces an excellent bacteria-inhibiting effect against *Escherichia coli* and *Staphylococcus aureus*. The antibacterial rates were 100% and 99.5%, respectively. Because the mutual solubility of silver and iron is very low in both the solid and liquid states, a silver-rich compound solidified and dispersed at the ferrite/austenite interface and the ferrite, austenite, and secondary austenite phases in silver-doped 2205 DSS. Doping 2205 DSS with silver caused the Cr_{eq}/Ni_{eq} ratio of ferrite to decrease; however, the lower Cr_{eq}/Ni_{eq} ratio promoted the rapid nucleation of γ_2-austenite from primary α-ferrite. After 12 h of homogenisation treatment at 1200 °C, the solubility of silver in the γ-austenite and α-ferrite phases can be increased by 0.10% and 0.09%, respectively. Moreover, silver doping was found to accelerate the dissolution of secondary austenite in a ferrite matrix during homogenisation.

1. Introduction

Bacterial infection is a serious issue among fields in which critical standards of sanitation must be maintained, such as the food processing and health care industries. Especially for hospital-acquired infections, bacterial spreading often occurs through contact with medical appliances. Antibacterial materials have been developed for countering this problem, and stainless steel with biological properties has been widely used.

Both silver and copper are antibacterial elements used in fabricating stainless steel. To obtain antibacterial properties through copper doping, Hong and Koo [1] administered an aging treatment to acquire a precipitate concentration of copper ions on the surface, as is the standard procedure for manufacture. However, doping stainless steel with silver can produce a superior antibacterial effect without aging treatment. Therefore, the application of Ag-doped steel has been extended to kitchens and food processing factories [2,3]. Many methods have been developed and adopted to produce antibacterial film on the surfaces of materials, such as ion implantation [4], chemical assembly [3], and plasma deposition [5,6]. These developments have been made in response to an observable loss of efficacy of antibacterial properties, once the thin antibacterial surface layer is damaged.

Duplex stainless steel (DSS) was developed to function in aggressive environments. It consists of an approximately equal proportion of an austenite phase and ferrite phase. This phase constitution provides excellent properties of hardness, toughness, and localised corrosion resistance [7–10]. It is the most widely used in pulp and paper industry, cargo tanks for ships and trucks, food processing equipment, and biofuels plants. According to Michiels et al. [11] and Fonnesbech Vogel et al. [12] reports, bacteria are a natural part of the raw materials for food production but can also reside in food-processing equipment where they can (re)contaminate food products. Ready to-eat foods are potentially high risk products since they do not receive further heat treatment before consumption. This makes them vulnerable to (re)contamination and, if storage conditions allow further growth of bacteria, they may cause disease in humans [13]. Therefore, reducing bacteria reside in food-processing equipment may prevent adhering to surfaces of food production by silver-containing stainless steel for antibacterial applications in food-processing industry. Up to now, the relative literatures of silver-containing duplex stainless steel (DSS) in antibacterial application is few to publish. This considered, the purpose of this study was to investigate the effect of silver on the microstructure and antibacterial rate by doping a 2205 DSS matrix with silver through melting and thus determine whether this process yields enduring antibacterial properties.

2. Experimental

2.1. Material preparation

2205 DSS was doped with 0.2 wt.% silver in this study. The chemical compositions of the steel are listed in Table 1, and the specimens were named 2205-Base and 2205–0.2 Ag. The materials were melted in a high-frequency induction furnace under a nitrogen atmosphere and homogenised at 1120 °C for 2 h to eliminate microsegregation after casting.

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Table 1
Chemical composition of 2205-Base and 2205–0.2 Ag duplex stainless steel unit: wt.%.

Specimens	C	Si	Mn	P	S	Cr	Ni	Mo	Ag	N	Fe
2205-Base	0.02	0.38	1.19	0.023	0.001	23.4	6.2	3.18	–	0.22	Bal.
2205–0.2 Ag	0.02	0.38	0.81	0.024	0.003	22.8	6.5	2.97	**0.19**	0.26	Bal.

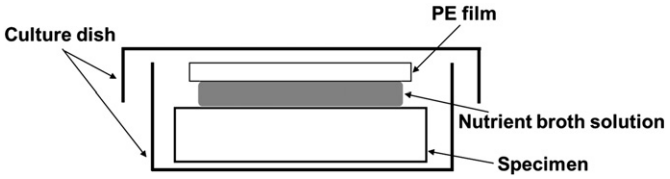

Fig. 1. Schematics of the film fabrication method.

2.2. Antibacterial property examination

The antibacterial procedure was carried out according to JIS Z2801: 2000 specifications. The solution-treated specimens were cut into squares with dimensions of 50 mm × 50 mm × 5 mm. The antibacterial specimens were polished, cleaned with acetone using an ultrasonic machine, and dried thoroughly. The test was performed using bacteria-containing solutions (suspensions) held in close contact with test surfaces. *Escherichia coli* ATCC6538P and *Staphylococcus aureus* ATCC6538P were used as test organisms in this study. *E. coli* and *S. aureus* were cultivated at 37 °C in a nutrient broth solution. The initial bacterial concentration was approximately 10^5 CFU mL^{-1}, and 0.4 mL of the bacterial suspension was then applied dropwise and spread over each sample to create a contaminated surface. The samples were subsequently covered by a sterilised polyethylene film (4 cm × 4 cm) to keep them in close contact with the bacterial suspension and incubated at 37 °C for 24 h. After incubation, 10 mL of the diluted bacterial suspension was pipetted onto nutrition agar plates to collect live bacteria. A schematic of the film fabrication method is shown in Fig. 1. The antibacterial rates can be calculated using the following formula:

$$\text{Antibacterial rate}(\%) = \frac{\text{N1-N2}}{\text{N1}} \times 100 \quad (1)$$

N1: number of viable bacteria adhered to specimens after 24 h of incubation.
N2: number of bacteria adhered to specimens after 24 h of incubation.

2.3. Homogenisation treatment

To investigate the microstructures of 2205-Base and 2205–0.2 Ag DSS, the specimens were placed in a box furnace for secondary heat treatment at 1200 °C. During homogenisation, the specimens were water quenched after 2, 4, 6, 8, 10, and 12 h treatment to prevent the reprecipitation of second phases.

2.4. Phase quantitation and microstructure examination

To examine the effect of silver doping on 2205 DSS, the Fischer Feritscope FMP30 was employed to measure variation in the δ-ferrite content after various homogenisation durations. The Feritscope operates by generating an alternating magnetic field in the sample which is proportional to the ferrite content and which the instrument can detect. As in metallography preparation, the 2205-Base and 2205–0.2 Ag specimens were ground using SiC abrasive papers to the #2000 grade and polished with 1.0- and 0.3-μm Al_2O_3 powder. An LB1 reagent solution (0.5 g of $K_2S_2O_5$ + 20 g of NH_4HF_2 + 100 mL of H_2O) was then used to etch phases. X-ray diffractometer (XRD; Bruker D8) was adopted to detect the structures with copper target and scanning rate of 0.05°. In addition, optical microscopy and field emission scanning electron microscopy (FE-SEM; Hitachi S-4800) with energy-dispersive spectroscopy (EDS) were employed to observe and analyse the microstructures. An electron probe X-ray microanalyser (JEOL JXA-8200) was also employed to examine the silver content by using wavelength-dispersive spectroscopy (WDS). In order to characterise the surface morphology of the 2205 DSS, atomic force microscopy (AFM; NT-MDT & NTFGRA Spectra-upright) was performed.

3. Results and discussion

3.1. Effect of silver doping on microstructure of 2205 duplex stainless steel

Phase identification is confirmed by X-ray diffraction patterns, as shown in Fig. 2. The major X-ray diffraction peaks are composed of ferrite and austenite. Due to low content of 0.2 wt.% in 2205–0.2 Ag DSS steel, the intensity is weak to detect the silver diffraction peak. In addition, γ (111) and α (110) peaks are the preferred orientation in 2205-Base and 2205–0.2Ag DSS steel, respectively. This indicates that the major diffraction peak of ferrite increased by doping of silver.

The typical microstructure of 2205 DSS after solution treatment, consisting of α-ferrite, primary γ-austenite (γ_1), and secondary γ-austenite (γ_2), is shown in Fig. 3. As described by Knyazeva et al. [10] and Rajasekhar et al. [14], the quasibinary section of the Fe—Cr—Ni phase diagram at 70% iron shows that 2205 DSS undergoes dual-phase

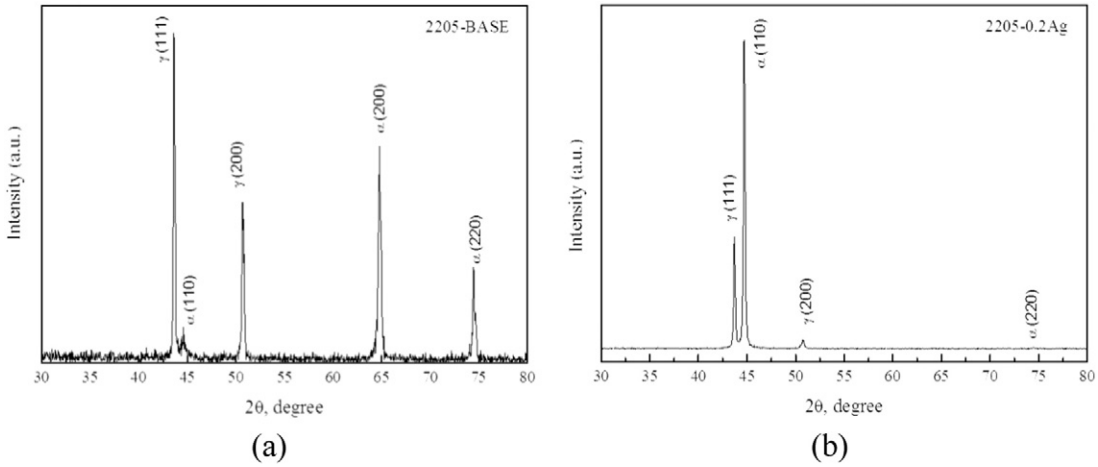

Fig. 2. X-ray diffraction diagrams of the duplex stainless steel: (a) 2205-Base; and (b) 2205–0.2 Ag.