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Effect of cold working on the corrosion resistance of JPCA stainless steel in flowing Pb–Bi at 450 °C

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ABSTRACT

Development of a high performance proton beam window material is one of the critical issues for the deployment of the accelerator-driven transmutation system (ADS) with liquid Pb–Bi eutectic as a spallation target and coolant. In the present study, we applied 20% cold work treatment to JPCA austenitic stainless steel and investigated it from the corrosion behavior viewpoint. The corrosion test of 20% cold-worked JPCA SS has been carried in the JLBL-1 (JAEA Lead–Bismuth Loop-1) apparatus. The maximum temperature, the temperature difference, the flow velocity and the exposure time of the liquid Pb–Bi were 450 °C, 100 °C, 1 m/s, and 1000 h, respectively. For comparison analysis, JPCA SS without cold working was also tested in the same time and conditions with the 20% cold-worked JPCA SS. The results showed a different corrosion behavior between the JPCA SS without and with cold working. As for the JPCA SS without cold working, Pb–Bi penetrated into the matrix through a ferrite layer which was formed because of constituent metals dissolution from the matrix into Pb–Bi. As for the 20% cold-worked JPCA SS, dissolution attack occurred only partially and formed localized superficial pitting corrosion. It was found that the different corrosion behavior occurred because the cold working induced a structure transformation from γ-austenite to α'-martensite and affected the corrosion resistance of the JPCA SS in flowing Pb–Bi at 450 °C.

1. Introduction

The accelerator-driven nuclear transmutation system (ADS) has been investigated and designed in Japan Atomic Energy Agency (JAEA) in order to reduce the burden for the geological disposal of the high level waste (HLW) [1,2]. In the design, molten Pb–Bi eutectic will be used as the spallation target, and high energy protons will be bombarded to the spallation target through a beam window. The proton beam window will be inserted at about 6 m in depth and submitted to the hydrostatic pressure of the molten Pb–Bi [3–5]. In order to reduce thermal stresses due to heat generation, the thickness of the proton beam window must be thin but also strong enough to endure the buckling pressure against the hydrostatic loading. The window has been designed so that the thickness at the bottom of the window is about 2 mm for the design condition, and then the window gradually becomes thicker toward the edge [3–5]. Consequently, the proton beam window will be exposed to environmental hazards, i.e., bombardment of high energy protons, irradiation by spallation and fission neutrons, corrosion attack of Pb–Bi, and hydrostatic pressure of liquid Pb–Bi. Hence, the development of a high performance material for the proton beam window is one of the critical issues for the development of the ADS. As one of candidates for the proton beam window material, JPCA (Japanese Primary Candidate Alloy) austenitic stainless steel, as a modification of 316 SS type, has been chosen [6]. The JPCA SS has been intensively investigated and developed for nuclear systems application [7–11]. Additionally, improvement of the performance of JPCA SS for nuclear systems applications has also been intensively developed, especially using the cold working technique [7–9]. The cold working improves the hardness and strength of the stainless steel, which is important for the critical parts in the nuclear systems. Nevertheless, investigation of the compatibility of the cold-worked JPCA SS to the liquid lead–bismuth environment has been limited [12]. Accordingly, the aim of this study has been to investigate the effect of cold working on the compatibility of JPCA SS in flowing Pb–Bi eutectic at 450 °C from a corrosion behavior viewpoint. The temperature was set as the practical operating condition of the proton beam window in the ADS design.

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2. Experiment and procedures

2.1. Experimental apparatus

The corrosion test was conducted in JLBL-1, which is the JAEA lead–bismuth loop for material corrosion. The schematic of the apparatus is shown in Fig. 1. The detail of the JLBL-1 apparatus has already been reported elsewhere [13]. The chemical composition of the Pb–Bi eutectic, in weight percentages, is 55.60% Bi, 0.0009% Sb, 0.0002% Cu, 0.0001% Zn, 0.0005% Fe, 0.0007% As, 0.0005% Cd, and 0.0001% Sn, with the balance being Pb. The surge tank was covered by 99.995% pure (by mass) argon gas during operation. During operation, the maximum temperature, the temperature difference, and the flow velocity of the liquid Pb–Bi at the specimen were 450 °C, 100 °C, and about 1 m/s, respectively. The corrosion test was carried out for 1000 h.

2.2. Materials

The tested materials were JPCA austenitic SS without and with cold working. JPCA is a revised 316 SS by the addition of Ti and C, in order to increase swelling resistance by decreasing the cavity-volume swelling in high He/dpa (displacements per atom) ratio environments [7]. The chemical composition in detail of the tested JPCA SS is shown in Table 1. The shapes of the tested materials were cylindrical tubes as shown in Fig. 2. Originally, the JPCA SS was in the shape of plates and was annealed at 1100 °C for an hour. Afterward, one of the plates was formed into a cylindrical tube. Another of the plates was 20% cold-worked and then formed into a cylindrical tube. Both of the cylindrical tubes were joined using TIG welding.

2.3. Experimental procedures

During this corrosion test, the oxygen concentration was not monitored online, because the oxygen sensor did not work well during this experiment. However, according to a previous experiment [14] in which the oxygen sensor had worked well and which had been carried out under conditions similar to those of the present experiments, it was probably that the oxygen concentration in the Pb–Bi in the present experiments was around 10^{-8} and 10^{-9} wt.%. After the corrosion test, the specimen pipe was cut into several pieces in the shape of rings. Then, the rings were cut in the middle. One side of each ring was used for micro structural and elemental analysis. The analyses were performed using Scanning Electron Microscopy (SEM)–Energy Dispersive X-ray Spectroscopy (EDS) and Atomic Force Microscopy (AFM). Another side of each ring was used for X-ray diffraction (XRD) analysis. For the SEM–EDS and AFM analyses, the specimens were mounted in resin and then polished with a mechanical grinder, first using polycrystalline diamond grains down to 1/4 μm in size and then finishing with suspension liquid. To analyze the grain structural changes of JPCA SS because of the cold working treatment, JPCA SS without and with cold working as received (without corrosion testing) were electrochemically etched using a liquid containing 62 vol.% nitric acid and 38 vol.% water. Then, the analysis was performed using Optical Microscopy (OM).

3. Results

3.1. Grain structure observations

Analysis of the grain structure of the JPCA SS without and with cold working (as received specimens) using OM are shown in

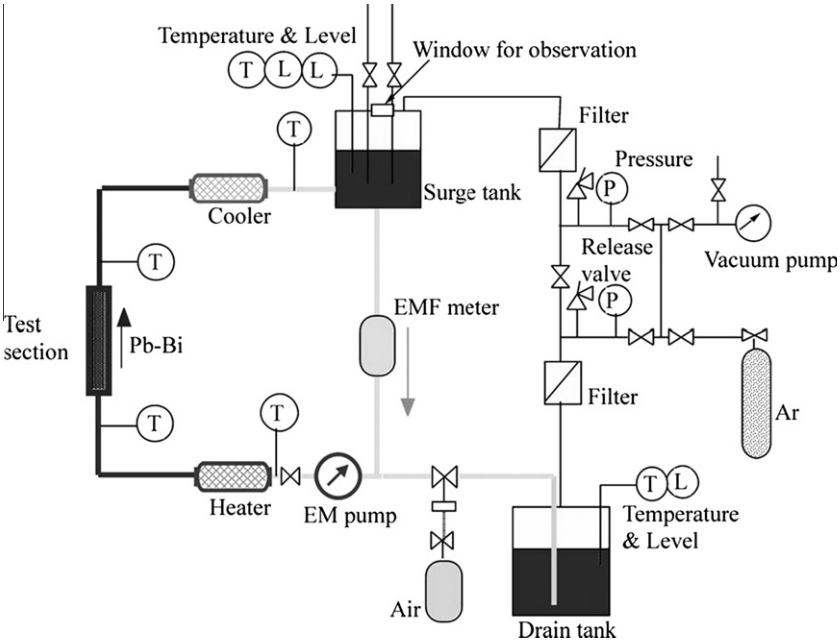

Fig. 1. Schematic of JLBL-1 corrosion test apparatus.

Table 1
Chemical compositions of JPCA stainless steel (unit: wt.%).

Fe	Ni	Cr	Mo	Mn	Si	Ti	C	B	P	Co	S	N
Bal.	15.60	14.53	2.50	1.48	0.52	0.24	0.053	0.004	<0.005	<0.005	0.0017	0.0012