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Effect of dissolved gas on mechanical property of sheath material of mineral insulated cables under high temperature and pressure water

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ABSTRACT

In terms of an applicability of mineral insulated (MI) cables under high temperature and pressure water such as coolants in nuclear power plants, effects of dissolved gases on mechanical properties of the sheath materials of the MI cables were investigated. Slow strain rate testing was performed for AISI 304 and 316 stainless steels under high temperature and pressure water at 325 °C and 15 MPa in pure water. At a strain rate of 5×10^{-3} mm/min with the condition, oxygen: ~8.5 ppm, hydrogen: <1 ppb, nitrogen: ~14 ppm, fully ductile fractures were observed. The tensile strengths increased with the change in the strain rate from 5×10^{-3} to 5×10^{-4} mm/min. On the other hand, with oxygen: <1 ppb, hydrogen: <1 ppb, nitrogen: ~30 ppm by nitrogen bubbling, partial brittle fractures were observed mainly near the edge of the samples. In addition, the change in the strain rate from 5×10^{-3} to 5×10^{-4} mm/min increased the rate of the brittle fracture surface and decreased the tensile strengths. The change in the dissolved hydrogen from <1 ppb to 50 ppb also increased the rate of the brittle fracture surface and decreased the tensile strengths.

The similar brittle behavior was observed by replacing nitrogen by argon bubbling. The results implied the possibility of embrittlement phenomena of the stainless steels in high-temperature and pressure water even with very low dissolved oxygen resulting in high susceptibility to hydrogen embrittlement.

1. Introduction

Mineral insulated (MI) cables are widely used in industrial fields because of their good heat-resistance, water-resistance, and mechanical properties. They are applied in nuclear facilities as power-, signal-, and measurement cables. For example, they will be applied as magnetic diagnostic coils for ITER [1]. The MI cables are composed of a single or a number of core wires with a high heat-resistant mineral insulator covered by a flexible metal sheath. In the nuclear industry, magnesium and aluminum oxides are usually used for the insulators because of their chemical stability, purity, and high melting point. For the sheath materials, austenite stainless steels and nickel base alloys are often used because of their good corrosion properties. If water cooling systems are adopted at demonstration power plants after ITER, a temperature of about 300 °C and a pressure of 15 MPa are considered as candidates for coolant water conditions. In the case of in-situ measurements using the MI cables in such a high temperature/pressure water environment, it is necessary to evaluate their fracture properties since the thickness of the sheath is typically only less than 1 mm. AISI 304 and 316, which are representative austenite stainless steels, are typical materials used for sheath materials of MI cables. Moreover, AISI 304 and 316 are widely studied at conditions of coolant of light water reactors. On the other hand, if water-cooling method is adopted for future practical fusion reactor, condition of coolant water is not decided. However, no studies have been performed on fracture properties of AISI 304 and 316 at very low DO condition. Therefore, we performed this study as the first step to investigate fracture properties of austenite stainless steels in high temperature/pressure water at very low DO condition.

The objective of this study is to investigate the effect of dissolved gases especially in the range of low dissolved oxygen on the fracture properties of AISI 304 and 316 stainless steels as sheath materials of the MI cable in pure water at 325 °C and 15 MPa.

2. Experimental

The materials used in this study were flat bars of two types of austenitic stainless steel (AISI 304 and 316 stainless steels). The chemical compositions of the steels are listed in Table 1.

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Table 1
Chemical composition of samples.

	C	Fe	Cr	Ni	Mn	Si	Mo	P	S
AISI 304	0.06	Bal.	18.9	8.06	1.85	0.21	–	0.040	0.006
AISI 316	0.04	Bal.	16.9	10.0	1.33	0.32	2.01	0.036	0.025

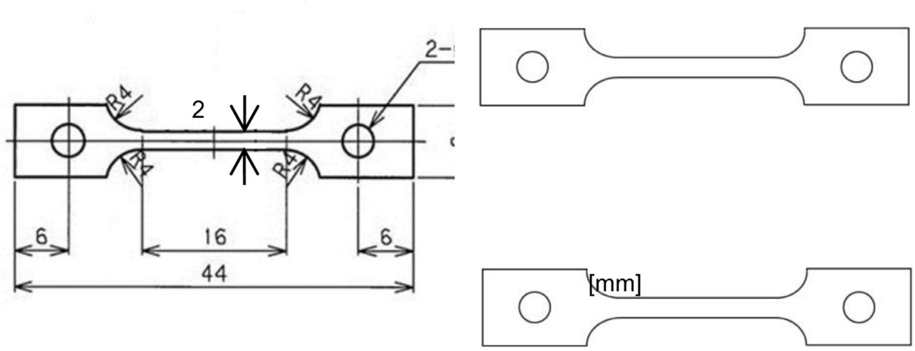
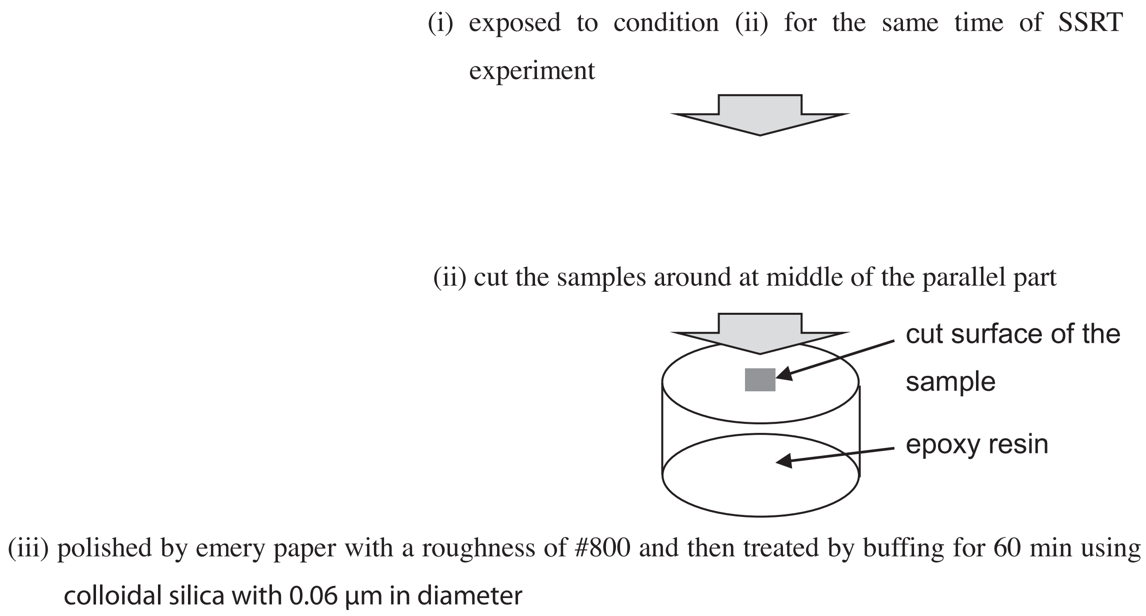


Fig. 1. Dimension of SSRT specimen.


(i) exposed to condition (ii) for the same time of SSRT experiment

(ii) cut the samples around at middle of the parallel part

(iii) polished by emery paper with a roughness of #800 and then treated by buffing for 60 min using colloidal silica with 0.06 μm in diameter

Fig. 2. Procedure of sample preparation for hardness test. The sample undergo a process (i)-(iii) and (ii)-(iii) was defined as “with N_2 bubbling” and “without N_2 bubbling”, respectively.

Slow-strain-rate testing (SSRT) samples were designed as small tensile specimens. The dimensions of the specimen are shown in Fig. 1. A high temperature and pressure water loop apparatus equipped with two autoclave units was used. Stress-strain curves were obtained by SSRT in one of the autoclave unit with pure water at 325 °C and 15 MPa. The strain rates of 5×10^{-3} and 5×10^{-4} mm/min were applied. Dissolved levels of oxygen and hydrogen were obtained by dissolved concentration meters, while the dissolved nitrogen and argon levels were estimated through calculations using the nitrogen partial pressure and its solubility in water. The dissolved gas concentrations were controlled at the following two levels, (i) Oxygen: 8.5 ppm, Hydrogen: <1 ppb, Nitrogen: $\sim$14 ppm as a reference condition in equilibrium with atmospheric air, and (ii) Oxygen: <1 ppb, Hydrogen: <1 ppb, Nitrogen: $\sim$30 ppm to investigate the effect of very low dissolved oxygen. In addition, the following conditions were applied as well: (iii) Oxygen: <1 ppb, Hydrogen: 50 ppb, Nitrogen: $\sim$30 ppm to investigate the effect of addition of hydrogen to condition (ii), and (iv) Oxygen: <1 ppb, Hydrogen: <1 ppb, Argon: $\sim$56 ppm to confirm that there is no effect of nitrogen gas used for concentration control of dissolved gas, with the first one being applied on the 316 stainless steel with a strain rate of 5×10^{-4} mm/min and the second one used for the 304 stainless steel with 5×10^{-3} mm/min as strain rate, respectively.

The fracture surfaces of the specimens were observed by scanning electron microscopy (SEM) to examine the fracture mode and the percentage of brittle fracture. In addition, micro-Vickers hardness tests were carried out by using a 100 g load with indentation loading for 15 s. Procedure of sample preparation for hardness test is shown in Fig. 2. Prior to the hardness tests, the samples were exposed to the pure water environment at 325 °C and 15 MPa with the dissolved gas condition (ii) and were cut vertical to the longitudinal direction of the samples around at middle of the parallel part. After being mounted into epoxy resin, the samples were polished with #800 emery paper and then treated by buffed finish for 60 min using colloidal silica with 0.06 μm in diameter. The hard-