

Correlation of Chemical Composition, Precipitate and Ductile Fracture Property of AISI Type 347 for Nuclear Piping

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1. Introduction

An adequate J-R fracture resistance at a reactor operating temperature is required to demonstrate the stability of a hypothetical flaw for an application of Leak-before-break (LBB) design concept to nuclear piping systems including Nb-stabilized austenitic stainless steel (AISI type 347) piping. It has been reported that type 347 has a reduced fracture resistance when compared to unstabilized austenitic stainless steels and it has shown a large degree of heat-to-heat variability in its fracture properties [1,2].

Variations in the fracture properties in austenitic stainless steels have been described as a function of the chemical composition, microstructure, specimen geometry and orientation in previous studies [1-3]. However, systematic investigations on a relationship between the chemical composition, microstructure and the ductile fracture properties of type 347 are scarce.

The purpose of the current work is to investigate the effects of the C, N and Nb contents on the J-R fracture resistance of type 347 at 316°C, which is a normal reactor operating temperature, through systematic tests and quantitative microstructural analyses.

2. Experimental

Ten heats of experimental type 347 steels were produced by vacuum induction melting and hot-rolled to 32 mm-thick plates. The test blocks which were taken from the plates were annealed at 1050°C for 1 hour. The results of the chemical analyses for the test materials are listed in Table 1. Nine heats of the test materials were designed to construct a matrix which was a combination of three carbon content levels and three nitrogen content levels. The heat, which is designated as MC-N2-1 in Table 1, was added to the matrix to investigate the effects of the niobium content on the fracture property of type 347 at fixed carbon and nitrogen contents.

1T-C(T) specimens, to measure the J-integral resistance (J-R) curves, were machined so as to the crack propagated in the L-T orientation. After the pre-cracking, the specimens were side-grooved to a total of 20 % of the thickness. The J-R tests were conducted at 316°C by using a 100kN-capacity servo-hydraulic test system.

Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) were used in conjunction with an energy dispersive X-ray spectrometer (EDS) to allow for a primarily identifica-

tion of the second phase particles in the experimental steels. In order to examine the 3-dimensional features of the fracture process, the fractured surfaces were sectioned along the crack propagation direction and the resultant surfaces were observed with SEM. Electrolytic extractions of the second phase particles were carried out for the quantitative analyses and identifications of the particles. The selected residues obtained from the electrolytic extractions were analyzed by X-ray diffraction (XRD) to determine the crystal structure of the particles.

Table 1. Chemical compositions of experimental type 347 stainless steels that varied in C, N and Nb contents.

Heat		(wt%)				
		C	N	Nb	Cr	Ni
low-C Series	LC-N1	0.020	0.030	0.26	17.81	10.04
	LC-N2	0.023	0.071	0.25	17.25	9.95
	LC-N3	0.019	0.110	0.24	17.63	10.01
med.-C Series	MC-N1	0.030	0.029	0.38	17.60	10.02
	MC-N2	0.028	0.068	0.37	17.26	9.97
	MC-N2-1	0.028	0.071	0.30	17.23	10.01
	MC-N3	0.033	0.103	0.37	17.77	9.98
high-C Series	HC-N1	0.049	0.033	0.63	17.62	9.97
	HC-N2	0.047	0.072	0.60	17.21	10.12
	HC-N3	0.049	0.110	0.63	17.60	9.95

3. Results and Discussion

Fine dispersed particles were found throughout the matrix of all the steel, however there was a large degree of heat-to-heat variability in the density of the coarse particles, which ranged in size from about 1 to 10 μm . From the TEM analyses, the finer particles, which averaged about 0.1 μm in size, were identified as Nb(C,N) and CrNb(C,N), while all the analyzed coarse particles were identified as Nb(C,N).

As a result of the XRD analysis for the extracted residue from the test materials, Nb(C,N) precipitates were found in all the test samples, while CrNb(C,N) precipitates were found only in the samples from the Low-C (low carbon) Series steels and MC-N3 steel. It means that CrNb(C,N)s were precipitated in the type 347 when the nitrogen to carbon content ratios were high. The quantity of filtered precipitates was affected by a combination of the carbon and nitrogen contents as shown in Fig. 1. The effect of niobium on the precipitate density is clearly observed as shown in Fig 1. The density of the precipitates in the MC-N2-1 steel, which contained a lower content of niobium at 0.03 wt%

carbon level, decreased to a half of a density of precipitate for the MC-N2 steel which contained a nominal content of niobium.

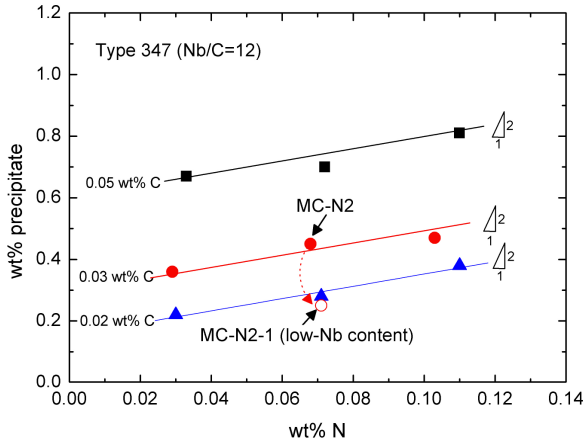


Fig. 1. Diagram showing the influences of C, N and Nb contents on the precipitate density in type 347 stainless steel.

There was a large variation in the J-R fracture resistance derived from the experimental steels at 316°C. The tearing modulus, which is an important material parameter for an LBB analysis, was measured for each J-R curve. The tearing modulus at a given amount of a crack extension, T_R which is defined as $(dJ/da) \cdot (E/\sigma_0^2)$ is indicative of the relative stability of a crack growth, where, E is elastic modulus and σ_0 is flow stress. It is widely accepted that a ductile material such as type 347 fails by a dimple rupture mechanism involving void nucleation, growth and coalescence in the plastic zone ahead of a crack tip [4]. Honeycombe and Bhadeshia [5] stated that a ductile crack growth, in the form of void coalescence, initiates at second phase particles (most likely carbides). The relationship between the density of the precipitates and the tearing modulus of the type 347 is presented in Fig. 2. The tearing modulus decreased as the density of precipitate decreased. It is deduced that a large amount of precipitate deteriorated the J-R fracture resistance of the type 347s.

To obtain direct evidence that the microstructural factors affected the fracture behavior of the type 347, the fractured J-R specimens were sectioned and examined with SEM in conjunction with EDS. Lines of the coarse particles were observed beneath the primary crack plane. It was observed that the coarse niobium-rich particles in the J-R specimen acted as void initiation sites and the cracks were propagated by coalescence of the voids as shown in Fig. 3. As the particles become larger, the voids formed ahead of the crack tip increased in size, and thus, the crack propagated with less energy. It is deduced that the ductile crack propagation in the specimens was accelerated by coalescence of the voids which were initiated by the decohesion of the matrix/coarse Nb(C,N) interfaces in the type 347s.

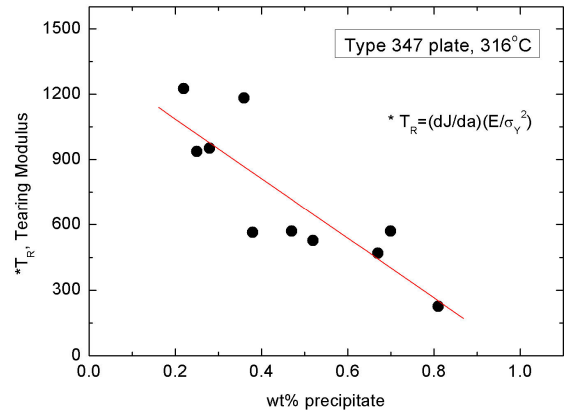


Fig. 2. Diagram showing that tearing modulus of type 347 stainless steel at 316°C decreases with increasing density of precipitate.

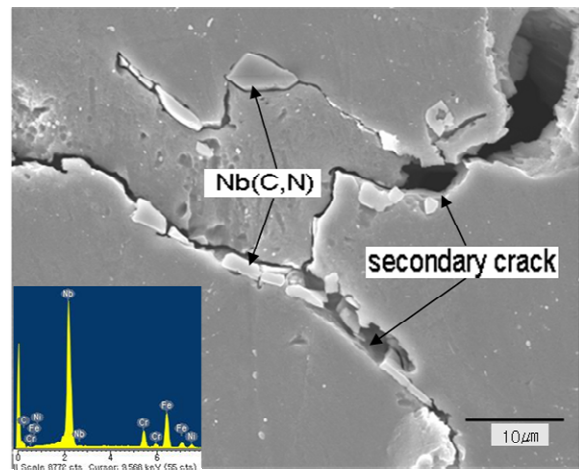


Fig. 3. SEM micrograph showing that linking of voids, which were initiated by coarse Nb(C,N) precipitates, propagated cracks in type 347 stainless steel.

4. Summary

It was observed that the density and size of the precipitates in the type 347 varied as a function of the carbon, nitrogen and niobium contents. The J-R fracture resistance decreased as the precipitate density increased. It is concluded that coarse niobium-rich precipitates are detrimental to the ductile fracture property of type 347 because they accelerated ductile crack propagation in it.

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