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Characterization of non-magnetic Mn–Cr steel as a low induced activation material for vacuum vessels

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Abstract

The JT-60SU (Super Upgrade) program is under discussion at Japan Atomic Energy Research Institute (JAERI). Its design optimization activity requires the vacuum vessel material to be non-magnetic, very strong and with low induced activation. However, there is no suitable material available to fulfill all the requirements. JAERI started to develop a new material for the vacuum vessel together with the Japan Steel Works (JSW). Chemical composition and metallurgical processes were optimized and a new steel named VC9, which has the composition of Cr – 16 wt%, Mn – 15.5 wt%, C – 0.2 wt%, and N – 0.2 wt% with non-magnetic single γ phase, was selected as a candidate material. Here, mechanical properties and weldability of VC9 were examined and the results were compared with those of type 316 or 316L stainless steel. It was shown that VC9 has good mechanical properties and weldability.

1. Introduction

The JT-60SU (Super Upgrade) program is being discussed at Japan Atomic Energy Research Institute (JAERI) [1]. Its design optimization activity requires the vacuum vessel material to be non-magnetic, very strong and with low induced activation. These properties are essential if we wish to decrease the weight of the vacuum vessel and of radioactive waste, to reduce exposure during maintenance, and to avoid interaction between the vacuum vessel and the magnetic field. However, since there is no suitable material available to fulfill all the requirements, JAERI started to develop a new material for the vacuum vessel together with the Japan Steel Works (JSW). Chemical composition and metallurgical processes were optimized and a new Mn–Cr steel named VC9 with non-magnetic single γ phase was selected as a candidate material [2,3]. In this study, VC9 was characterized from the aspects of mechanical properties and weldability. The results obtained are compared with those of 316 or 316L stainless steel.

2. Experimental

2.1. Materials

A new Mn–Cr steel named VC9 was selected for study. The nominal composition of the steel was Cr – 16 wt%, Mn – 15.5 wt%, C – 0.2 wt%, and N – 0.2 wt%. The steels used in this study were obtained by melting 25–50 kg at a time in a high frequency induction furnace in the time period 1996–1998. The detailed fabrication processes have been reported elsewhere [2,3]. The chemical composition of VC9 and type 316L steel used in this study are listed in Table 1.

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Table 1
Chemical composition of VC9 and type 316L steel (wt%)

		Mn	Cr	Ni	Mo	C	N	Si	P	S
VC9	Nominal	15.5	16.0	–	–	0.20	0.20	0.30	–	–
	Product (1996)	15.31	16.02	0.01	–	0.21	0.205	0.30	0.026	0.005
	Product (1997)	15.50	16.03	0.02	–	0.20	0.226	0.27	0.024	0.004
	Product (1998)	15.90	16.00	0.01	–	0.19	0.190	0.28	–	–
Type 316L steel	JIS spec.	<2.00	16–18	12–15	2–3	<0.03	–	<1.00	<0.0045	<0.03
	Product	1.07	17.16	12.07	2.14	0.011	0.07	0.51	0.021	0.001

2.2. Mechanical property tests

To evaluate mechanical properties of VC9, tensile, Charpy impact, low-cycle fatigue and fracture toughness tests were performed. Tensile tests were done in air at temperatures from room temperature (RT) to 773 K. The test pieces were 3∅ × 33 mm gage length (GL). Charpy-impact tests were done in air at RT on half-size specimens. Tensile and Charpy-impact tests were also performed for type 316L steel. Low-cycle fatigue tests were performed at RT in a vacuum on specimens of 10∅ × 25 mm GL. Fracture toughness tests were performed in air at temperatures from RT to 573 K on 1.0 T CT (compact tension) specimens. The test method was based upon ASTM E813-89 single-specimen technique.

2.3. Weldability tests

Weldability of VC9 using tungsten inert gas (TIG) or electron beam (EB) welding was investigated by metallographic observation, hardness tests and ferrite content measurement. Non-filler TIG welding was performed. The welding conditions were 120 A and 0.2 m/min, for current and welding speed, respectively. The welding conditions for EB welding were 140 mA and 0.4 m/min, in a vacuum. Hot cracking susceptibility for TIG welding was evaluated by the trans-varestraint test [4,5].

3. Results and discussion

3.1. Mechanical properties

Figs. 1 and 2 show the test temperature dependence of tensile properties of VC9. It is clearly seen that VC9 has high strength and good ductility from RT to 773 K. At the operating temperature of JT-60SU (573 K), tensile strength and 0.2% proof stress of VC9 were about 40% higher than those of 316L steel. The density of VC9 and 316L were 7.8 and 8.0 kg/m^3, respectively; therefore, VC9 has a higher specific strength than 316L steel. This fact allows us to decrease the weight of the vacuum vessel, as well as the amount of radioactive waste. An elongation of 60% at 573 K, about 50% higher than that of 316L steel, was considered a good enough ductility for a structural material.

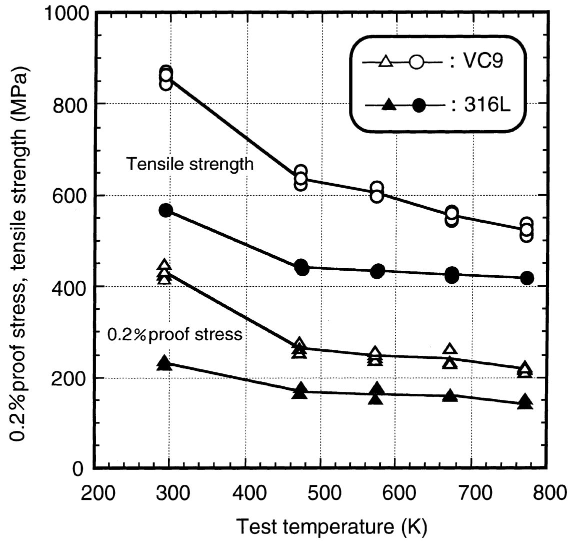

Fig. 1. Test temperature dependence of strength of VC9 and 316L steel.

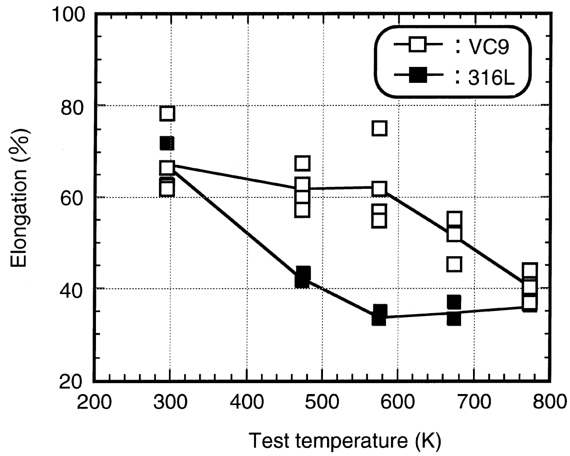

Fig. 2. Test temperature dependence of elongation of VC9 and 316L steel.

Table 2
Results of Charpy-impact tests (test temperature: 293 K)

	Absorbed energy (J)	Impact value (kJ/m^2)	Percent of ductile fracture (%)	Lateral expansion (mm)
VC9	85	2110	100	1.78
	83	2060	100	1.69
	82	2040	100	1.60
	84	2070	100	1.80
Mean value	83.5	2070	100	1.72
Type 316L[a]	133	3320	100	2.16

[a] Mean value of 6 TP.

The results of Charpy-impact tests are shown in Table 2. The impact values of VC9 were lower than that of 316L steel. Fig. 3 shows a scanning electron microscopy (SEM) photograph of the fracture surface of an impact-tested specimen. There are non-metallic inclusions several microns in size at the bottom of the dimples. It is thought that these non-metallic inclusions are responsible for the reduced impact values. The ratio of ductile fracture to the total surface area was 100% at RT.

The results of fracture toughness tests are shown in Fig. 4. The J_{IC} value of VC9 at RT was twice as high as those for 316L steel measured by another method [6]. It is thought that the above-mentioned non-metallic inclusions would probably not reduce the J_{IC} value of VC9. Fig. 5 shows the strain–number of cycles to failure (S–N) curve obtained by low cycle fatigue tests. The total strain amplitude $\Delta\varepsilon_t$ was fitted to Manson–Coffin's formula as follows:

$$\Delta\varepsilon_t = 46.482 Nf^{-0.4312} + 0.902 Nf^{0.0803},$$

for 316L steel [7]

$$\Delta\varepsilon_t = 22.772 Nf^{-0.4164} + 1.7485 Nf^{-0.1884}.$$

It was found that the fatigue life of VC9 is twice as long as that of 316L steel at RT for the same strain amplitude. These results suggest the high reliability of VC9 as a vacuum vessel material.

3.2. Weldability

From the metallographic observation for TIG and EB welds, neither cracks nor porosity was found around the weld zone. At the deposited metal for TIG, a small quantity of ferrite and about 2% of a non-magnetic

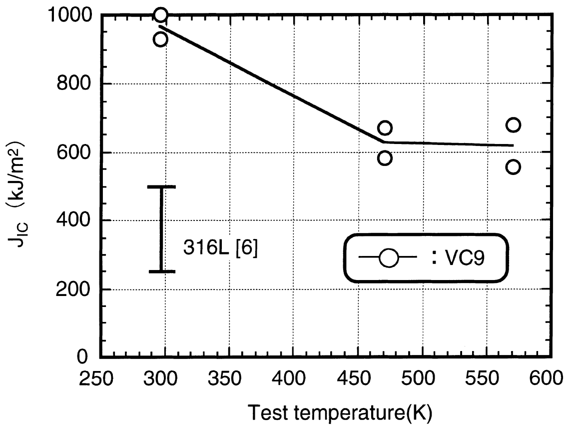

Fig. 4. Test temperature dependence of J_{IC} value of VC9.

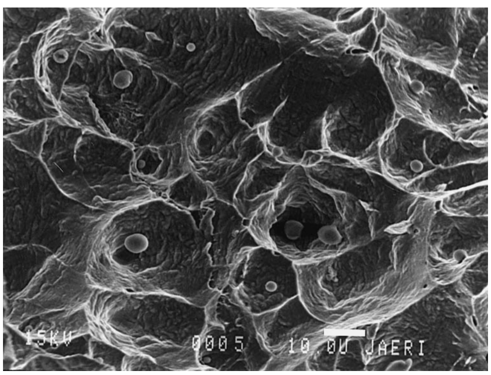

Fig. 3. SEM photpgraph of fracture surface after Charpy-impact test.

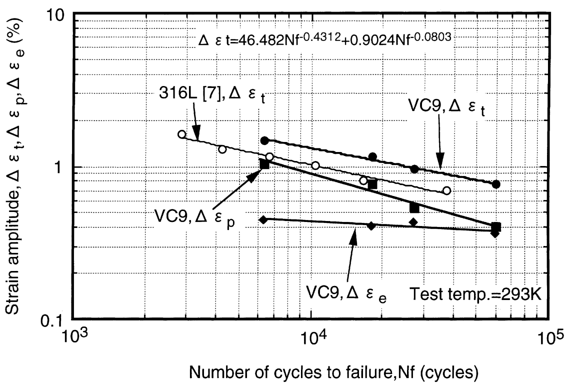

Fig. 5. Results of low cycle fatigue tests (S–N curve).

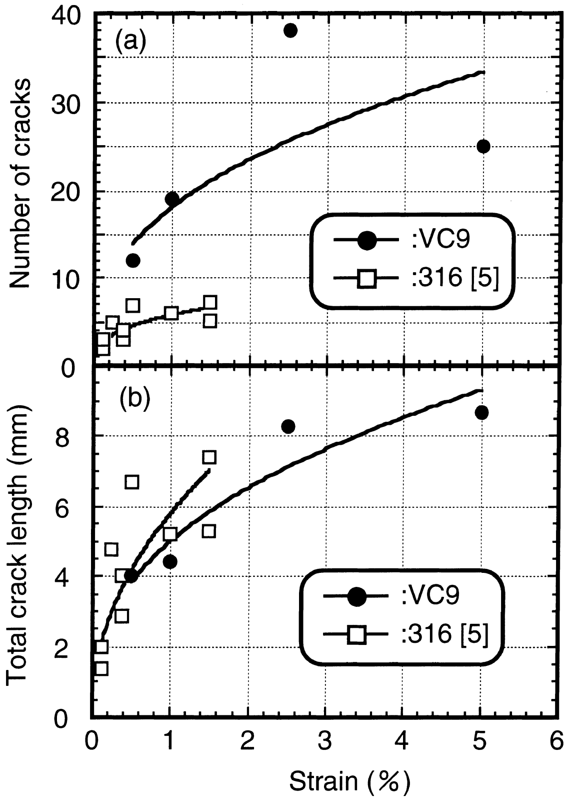

Fig. 6. Results of trans-varestraint test: (a) number of cracks; (b) total crack length.

phase, probably σ phase, were detected. At the heat affected zone (HAZ) for TIG, no ferrite was detected. For EB welding, no ferrite was detected in the deposited metal or HAZ. From the results of hardness measurement across the EB welded joint, the increase of Vickers hardness was typically between 20 and 50 mHv and no abnormal hardening was observed around the deposited metal or HAZ.

Fig. 6 shows the results of the trans-varestraint tests on the relationship between the additional strain and (a) the number of cracks, (b) the total crack length. In comparison with the literature value of 316 steel [5], the number of cracks for VC9 were several times larger than those for 316 steel, but the total crack length in VC9 was approximately the same as that of 316 steel. In the case of VC9, a large number of small cracks were generated, while in the case of 316 steel, a small number of large cracks were generated.

4. Conclusion

VC9 was characterized with regard to mechanical properties and weldability. The results obtained are as follows:

1. VC9 has higher tensile strength and 0.2% proof stress than 316L steel, and sufficient ductility from RT to 773 K. Because of non-metallic inclusions, the impact energy of VC9 was lower than that of 316L steel. Fracture occurred in a 100% ductile manner at RT.
2. The J_{IC} value of VC9 is twice that of 316L steel at RT. The fatigue life of VC9 is twice that of 316L steel at RT for the same strain amplitude.
3. VC9 showed good weldability in the case of TIG and EB weldings. The Trans-varestraint tests showed that the number of cracks in VC9 was several times larger than that of 316 steel but the total crack length was approximately the same.

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References

[1] K. Ushiga, G. Kurita, N. Toyoshima et al., IAEA-F1-CN-69/FTP/12 (1998) S.
[2] Ishiyama, M. Eto, K. Fukaya et al., J. At. Energy Soc. Jpn. 42 (2) (2000) 116 (in Japanese).
[3] H. Takahashi, Y. Shindo, H. Kinoshita et al., J. Nucl. Mater. 258–263 (1998) 1644.
[4] W.F. Savage, C.D. Lundin, Welding J. 44 (1965) 433S.
[5] T. Senda et al., Trans. JWS 2 (2) (1971) 45.
[6] K. Machida, M. Kikuchi, H. Miyamoto, Nihon Kikai Gakkai Ronbunshuu A 53 (1987) 1362.
[7] The Japan Welding Society, JWES-AE-9803, p. 122.