High-temperature Stress Rupture Performance of Hastelloy C-276

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Abstract

Hastelloy C-276 is one of the candidate cladding materials in supercritical water cooling reactor (SWCR). In this study, the SEM and TEM were used to investigate the microstructure of C-276 alloy before and after ruptured at 650 ℃ under different tensile stresses. Based on the experimental results, it can be concluded that the C-276 alloy has a good high-temperature stress rupture performance which is speculated to be the co-effects of solid solution-strengthening, precipitation-strengthening and deformation twin-strengthening.

1. Introduction

The China Department of Science and Technology has recently initiated a project aimed at identifying and developing the materials needed for the construction of the critical components of supercritical water cooling reactor (SWCR) for advanced nuclear power plant. The materials most withstand team conditions of 600℃/25MPa which is more rigorous than the coolant condition of conventional reactors 330℃/15MPa. The current used materials, especially the cladding materials (Al, Zr alloys) of the fuel element, cannot meat the requirements of high temperature corrosion and strength proposal for a SCWR. T91, AL6XN, Hastelloy C-276 and some ODS-steels have been proposed as candidate materials for the cladding.

Hastelloy C-276 is a nickel-based superalloy derived from the Ni-Cr-Mo ternary system by addition of W and Fe alloying components. It is nominally a single-phase face-centered-cubic structure, solid-solution strengthened alloy not hardenable by conventional aging treatment [1]. This material has found widespread applications in chemical, aerospace and nuclear industries because of its good high temperature creep properties and excellent resistance to oxidation and corrosion in severely aggressive environments [2-7].

The welding metallurgy and the aging characteristics of Hastelloy C-276 have been investigated in some detail [8-12]. Precipitation of intermetallic phases P, μ and carbides have been observed in Hastelloy C-276 during different aging conditions. Leonard [8] has shown that the P-phase can precipitate during heat treatment at 875℃, and the P-phase can transform to the μ -phase after long times. Tawancy [9] has reported that $M_{12}C$ and Mo-phase were precipitated on the boundary after 1000 h aging at 537℃. Akhter [10] found that hardening phases (P, μ and M_6C carbide) are not produced at 650℃ for aging times up to 240 h but they are observed after long aging time of 1000 h at the same temperature. So far microstructure changes in Hastelloy C-276 during high temperature creep and the effect on the strength have not been reported.

In the present study, the persistent resistance of Hastelloy C-276 is tested at 650℃. The microstructure evolution after the test was observed and the effect of the subsequent microstructure on the strength is discussed.

2. Experimental procedure

2.1. Material and heat treatment

The C-276 alloy investigated in this research is of commercial grade and its chemical composition is listed in Table 1. The as-received ingots were cylindrical bars 20 mm diameter and produced by hot-rolling. The final treatment was solution annealing at 1170℃ for 0.7 h, and then quenched by water.

Table 1 Chemical composition of C-276 alloy in wt%

Ni	Cr	Mo	Fe	W	Mn	V	Cu	Co	Si	C
Bal.	**16.01**	**16.03**	**5.41**	**3.23**	**0.29**	**0.17**	**0.10**	**0.07**	**0.05**	**0.005**

2.2 High temperature persistent resistance test

Specimens 5 mm in gauge diameter and 100 mm in gauge length were machined from the as-received ingots based on the China test standard GB/T2039－1997. The persistent resistance tests were carried out in air at 650℃ under the stresses of 430, 400, 300 and 260 MPa. The tensile extension was measured by extensometers placed on samples projections.

2.3. Microstructure characterization

Samples were sectioned for observation of the microstructure evolution. Microstructure was studied by a field emission high resolution SEM (Sirion 200) and a TEM (JEOL 2010) equipped with an energy dispersive spectrum (EDS) analysis system. The SEM specimens were prepared using a conventional mechanical polishing followed by etching with a solution of HCl = 30 ml, HNO_3 = 10 ml and $FeCl_3$ = 5 g. The TEM specimens were finally electrolytically thinned by the double-jet technique using a solution of 3% perchloric acid and 97% methanol at -20—-30 ℃. The thinning voltage was set at 50 V for 30 s.

3. Results and discussion

3.1 High temperature persistent resistance

Fig.1 shows the results of rupture stress vs. time measurements of Hastelloy C-276 tested at 650℃ under different stresses of 430, 400, 300 and 260 MPa. The corresponding rupture times are 76, 143, 400 and 650 h, respectively. For the purpose of comparison, the curves for Inconel-690 and Inconel-600 alloys are also shown in the same figure. Among the alloys, C-276 shows the highest persistent resistance within rupture time of 1000 h. Inconel-690 and Inconel-600 alloys have similar strength while the strength of C-276 is more than double.

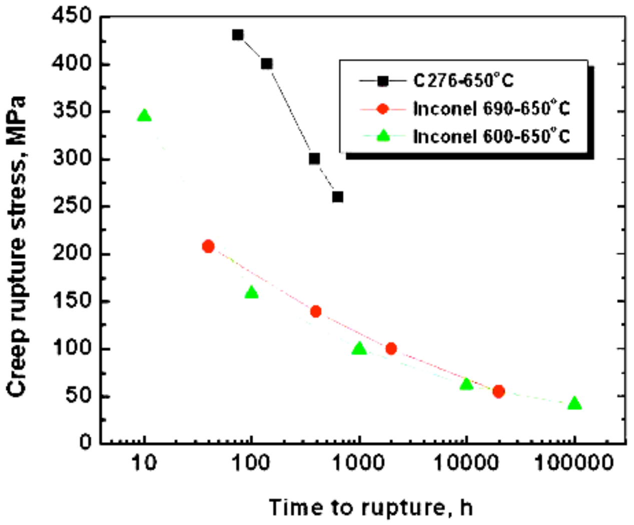


Fig.1 Rupture stress vs. time of C-276 alloy tested at 650℃ under various stresses, compared with Inconel-690 and Inconel-600 alloys.

3.2 Microstructure characterization

Hastelloy C-276 is known to have a single phase face-centered-cubic structure. Fig. 2 shows SEM morphology of the as-received Hastelloy C-276 before testing. The material consists of γ austenite grains and the austenite grain size ranges from 30 to 100 μm. Some annealing twins are present within the grain. Fig. 3(a) shows the TEM bright field image of the as-received Hastelloy C-276. The microstructure shows a large number of tangled dislocations and networks of dislocations in the grains. Fig. 3(b) shows the corresponding selected area diffraction pattern (SADP) taken from the indicated spot in Fig. 3(a), showing a twin structure on the boundary. These numerous crystal defects might be formed during the heat treatment of the solution annealed at 1170℃ for 0.7 h and then quenched by water.

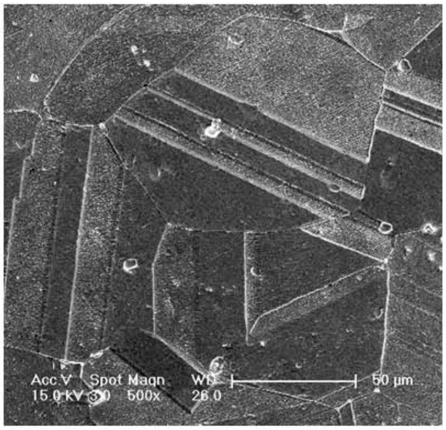


Fig.2 SEM image of as-received C-276 alloy.

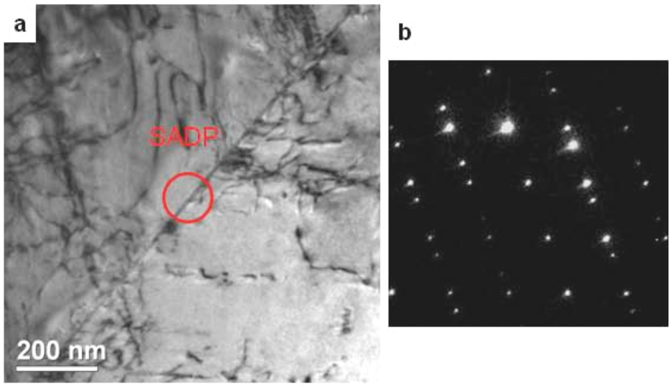


Fig.3（a）Bright-field TEM image of as-received C-276 alloy; (b) Selected area diffraction pattern (SADP) taken from the grain boundary spot indicated in (a).

To investigate the microstructure evolution of C-276 alloy after stress rupture test, the cross-section specimens cut from the ruptured samples were characterized by SEM. Fig. 4 shows the SEM morphologies of ruptured specimens at 650℃ under stresses of (a) 430 MPa (t_r=76 h); (b) 400 MPa (t_r=143 h); (c) 300 MPa (t_r=400 h); and (d) 260 MPa (t_r=650 h). Deformation twins were present in all four specimens. The high density of twins formed under the higher rupture stress indicated that the formation of the twins is associated with the high strain rate. The strength is enhanced by the twin formation as the effect of the refined crystalline strengthening.

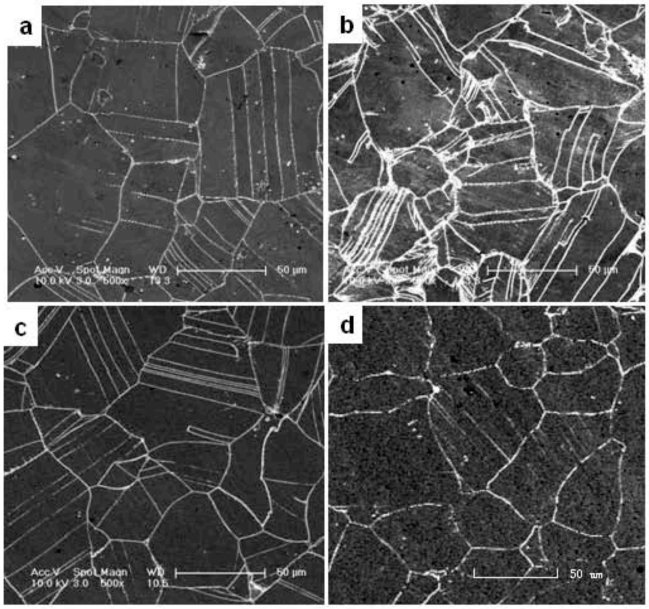
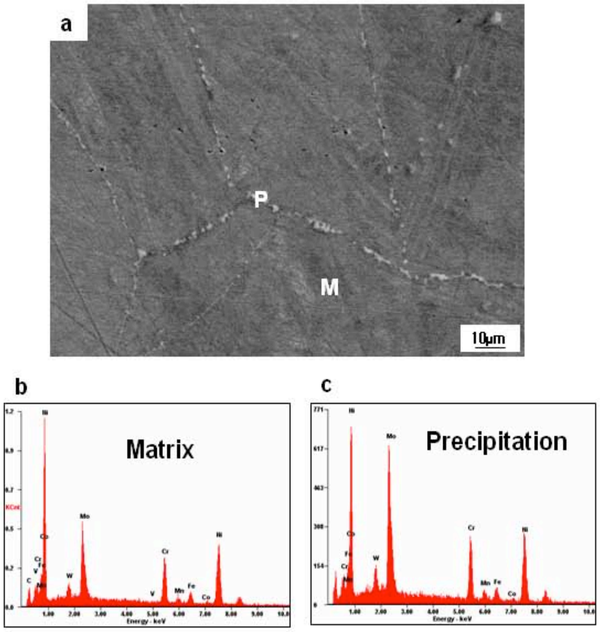


Fig.4 SEM cross-section investigations of specimens ruptured at 650℃ under（a）430 MPa (t_r=76 h); (b) 400 MPa (t_r=143 h); (c) 300 MPa (t_r=400 h); and (d) 260 MPa (t_r=650 h).

In order to distinguish the different precipitates, backscattering electron images (BEI) were taken on the cross-section specimens ruptured at 650 ℃ under stresses of 430 MPa (t_r=76 h), as shown in Fig. 5(a). Very fine precipitate particles are observed on the specimen, especially on the grain boundaries. Fig. 5(b) and (c) are EDS patterns taken from the matrix and precipitates, and (d) is the comparison of the chemical compositions of the main elements between matrix and precipitate by ZAF calculation. Although the precipitates formed mainly on the boundaries, some fine particles can be observed in the grain. Compared with the matrix, the precipitates contain higher concentrations of Mo, W and C. It is suggested that some kind of carbides must be formed.



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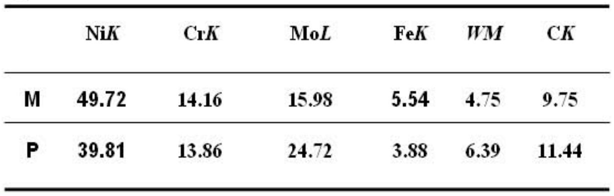

	NiK	CrK	MoL	FeK	WM	CK
M	49.72	14.16	15.98	5.54	4.75	9.75
P	39.81	13.86	24.72	3.88	6.39	11.44

Fig.5 C-276 ruptured at 650□ under 430 MPa (t_r=76 h)（a）Back scattering image; (b) EDS of the matrix; (c) EDS of the precipitates; (d) Comparison of the composition between the matrix and the precipitates.

Fig. 6 shows the TEM morphology and the SADP of the precipitates. The phase is identified as M_6C. M_6C carbide forms in alloy systems containing Mo or W in excess of about six percentage [10]. The carbide has a diamond cubic crystal structure (a ≈ 1.08-1.12 nm), and its lattice parameter is close to the chromium rich $M_{23}C_6$ carbide which has a face centered cubic crystal structure (a ≈ 1.06 nm). It is known that fine precipitates are contribute to the strength of the alloy during deformation.

Hastelloy C-276 is a solid-solution strengthened alloy. Solid-solution additions can increase the strength by a variety of mechanisms, such as segregation to stacking faults, interaction with vacancies and dislocation jogs and segregation to grain boundaries so as to influence grain-boundary sliding and migration, etc. Based on the above results, deformation twins and precipitates are also formed during the persistent resistance tests, which are thought to enhance the alloy during the deformation process.

4. Conclusions

Based on the investigation of the stress rupture performance and microstructure of the ruptured specimen, we propose Hastelloy C-276 as the promising candidate cladding material for SWCR. In particulars, the following conclusions can be made.

(1) Hastelloy C-276 shows a high persistent resistance under the temperature of 650℃.

(2) Deformation twins and fine precipitation particles are observed to form during the persistent resistance test.

(3) The mechanism of high-temperature persistent resistance of the C-276 alloy is speculated to be the co-effects of solid solution-strengthening, precipitation-strengthening and deformation twin-strengthening.

5. References

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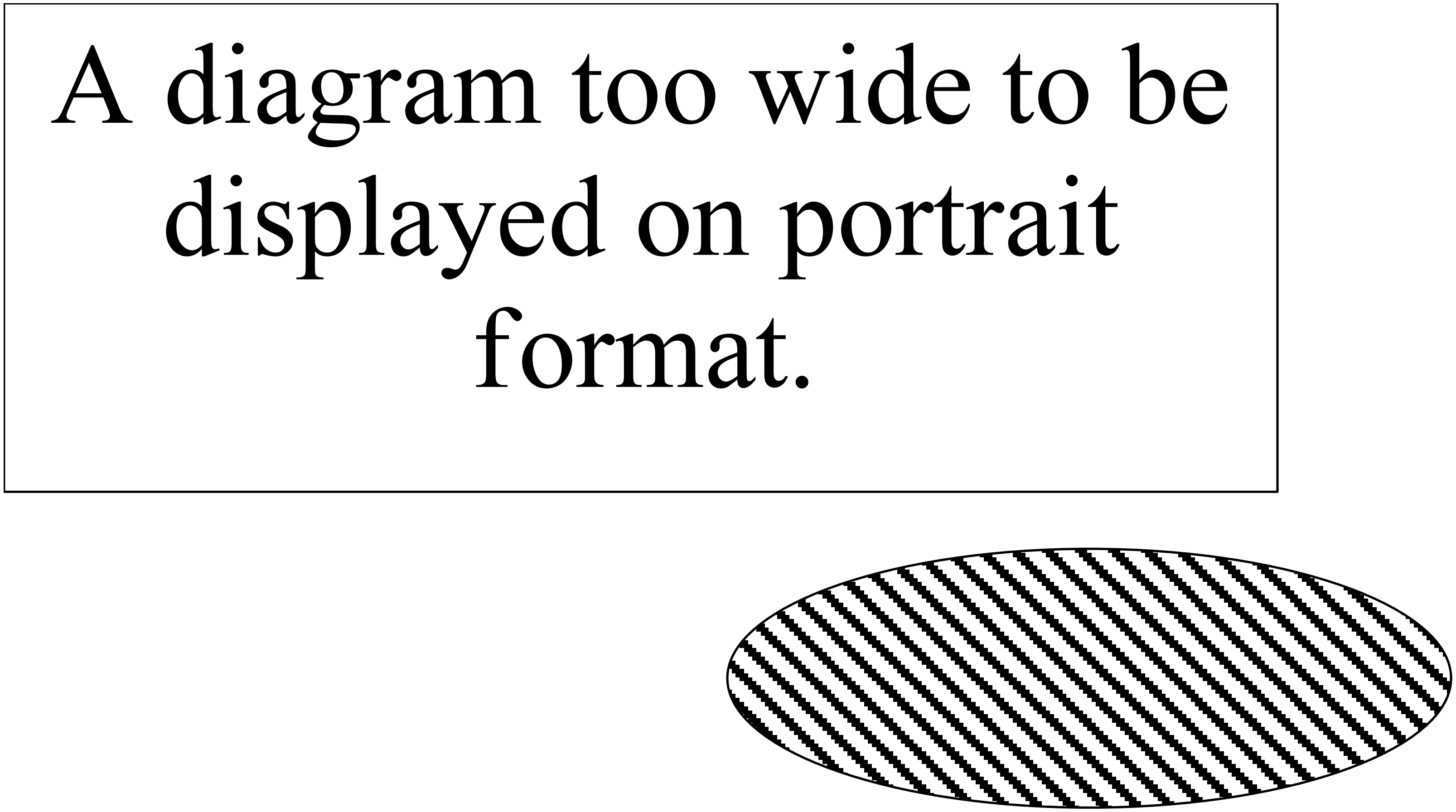

Figure 1 Example of a diagram too wide for portrait orientation

3. Conclusion

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