PAPER

High-temperature corrosion resistance of nickel-base alloy 617 in supercritical carbon dioxide environment

Zhiyuan Liang1, Yong Gui and Qinxin Zhao1

Key Laboratory of Thermal Fluid Science and Engineering of MOE, School of Energy and Power Engineering, Xi’an Jiaotong University, Xi’an 710049, People’s Republic of China

1 Authors to whom any correspondence should be addressed.

E-mail: liangzy@xjtu.edu.cn and zhaoqx@xjtu.edu.cn

Keywords: corrosion, metals and alloys, supercritical carbon dioxide, 617

Abstract

Corrosion behavior of Inconel 617 in supercritical carbon dioxide at 650 °C and 15 MPa for 1000 h was investigated. X-ray diffraction, high-resolution transmission microscopy, and Raman spectrum were used to observe and analyze the corrosion products formed on Inconel 617. The results showed that the corrosion products formed on Inconel 617 were composed of a thick Cr2O3 layer, a thin Al2O3 layer and a carbon-penetrated zone from the interface between carbon dioxide and the oxide scale to the substrate. Carbon was deposited on the surface of the oxide scales, which was verified by Raman results. The oxidation of Inconel 617 suffered in supercritical carbon dioxide was more serious than the carburization of Inconel 617.

1. Introduction

Supercritical carbon dioxide cycle attracts increasing attention worldwide due to its high efficiency, lower occupied space and huge water conservation [1, 2]. The corrosion of structural materials in supercritical carbon dioxide plays a key significance in the materials selection, the corrosion life prediction and even long-term safe operation of this new cycle. Therefore, research on the corrosion performance of structural materials is meaningful and urgent. Research was conducted on high-temperature corrosion of 9%–12%Cr and austenitic heat-resistant steels and nickel base alloys in various environments [3–12]. Saunders reviewed the effect of water vapor on the corrosion behavior of steel and metal [13]. Viswanathan summarized the steam oxidation of heat-resistant steels and alloys in supercritical water [14]. Bruce et al systematically investigated the corrosion behavior of typical heat-resistant steels and high-temperature alloys in supercritical carbon dioxide [7, 15]. They evaluated the corrosion resistance of investigated materials and summarized the effect of alloying elements on the corrosion rate in different environment. David et al studied that the corrosion behavior of Fe–Cr–X alloys in the various corrosive environments containing CO2 and obtained the corrosion kinetics and mechanism [6, 16, 17]. Lee researched the corrosion behaviors of several high Cr alloys in high-temperature supercritical carbon dioxide at different pressures [4, 18, 19]. Inconel 617 has an excellent strength property and poses a great corrosion resistance in high-temperature supercritical fluids. This alloy has been intensively used to the energy-conversation system. However, limited literature was focused on the corrosion behavior of Inconel 617 in supercritical carbon dioxide. Bruce et al studied the corrosion resistance of several high-temperature alloys including CCA617 in supercritical carbon dioxide and compared the weight gain of these alloys. The corrosion behavior and the corrosion products of Inconel 617 in supercritical carbon dioxide were not mentioned until now.

So, the corrosion behavior of Inconel 617 in supercritical carbon dioxide at 650 °C and 15 MPa for 1000 h was investigated. The aim of this research is to acquire the corrosion behavior of Inconel 617 and reveal the corrosion mechanism.
2. Experimental system and materials

The corrosion system is used to evaluate the corrosion resistance of steels and alloys in high-temperature supercritical carbon dioxide, as shown in Figure 1. Before corrosion testing, sufficient ultra-pure carbon dioxide was introduced to empty the residual air in the supercritical carbon dioxide corrosion platform. The test temperature was increased from 20 °C to 650 ± 0.1 °C. Research-grade carbon dioxide (99.999%) was imported in a liquid state by an SCF-24 supercritical carbon dioxide pump. The preheater was employed to heat the liquid carbon dioxide, and the designed temperature of the preheater was 700 °C. The flow rate of supercritical carbon dioxide was about 2 ml min⁻¹. The back pressure valve was installed to control the entire pressure of this system at the level of 15 ± 0.2 MPa. Experimental temperature and pressure of this corrosion experiment were 650 °C and 15 MPa, respectively. Investigated material was nickel-based alloy 617, which have been widely used in various energy and power systems. Its chemical compositions were as follows: 21.88 Cr-54.72 Ni-11.93 Co-8.8 Mo-0.06 C-0.1 Si-0.01 Mn-0.93 Al-0.39 Ti (wt%). X-ray diffraction (XRD), Raman spectrum (RS) and glow-discharge optical emission spectrometry (GDOES), high-resolution transmission electron microscope (HRTEM) are employed to characterize the corrosion products formed on Inconel 617 including their composition and distribution.

3. Results and discussion

Figure 2(a) shows the weight gain of Inconel 617 in supercritical carbon dioxide at 650 °C and 15 MPa for 1000 h. The corrosion kinetics of Inconel 617 followed a sub-parabolic corrosion law, which is similar to that of heat-resistant steels under the same condition. Numerous tiny oxides were observed on Inconel 617, as shown in figure 2(b). These oxides were mainly Cr₂O₃, which was confirmed by x-ray diffraction analysis, as shown in figure 2(c). What’s more, the intensity of Cr₂O₃ peaks increased with experimental time, indicating that the oxide scales became thicker, as shown in figures 2(c) and (d). However, the distribution and the thickness of oxide scales can not be obtained.

To figure out the insight detail of the corrosion products formed on Inconel 617, the focused ion beam technology and HRTEM were employed to characterize the corrosion products. Figure 3 shows the cross-sectional morphology and the EDS analysis of Inconel 617 exposed to supercritical carbon dioxide for 1000 h. A uniform oxide scale was observed on Inconel 617, as shown in figure 3(a). The EDS line and mapping result show the oxide scales were mainly composed of Cr, O and Al, as shown in figures 3(b) and (c). Underneath the oxide scale containing Cr and O, a narrow Al-rich oxide scale was detected, as shown in figure 3(c).

We chose the interplanar spacing calculated by HRTEM figures to ascertain the phase composition of oxide scales. The interplanar spacing of Cr-rich and Al-rich oxides were 2.66 nm and 3.48 nm in figures 3(e) and (f), which confirmed that the oxide scales were Cr₂O₃ and Al₂O₃ from gas/oxide interface to the substrate. The partial pressure of oxygen for Cr₂O₃ is much higher than that of Al₂O₃ [20]. The formation of Al₂O₃ was ascribed to the lower partial pressure of oxygen, which was decreased by a compact Cr₂O₃ layer [13].

Compared with the published data [4, 19], the oxide scale thickness of Inconel 617 was the thinnest, as shown in figure 4. Our data provided a guiding significance for the materials selection and the prediction for corrosion life, although some discrepancies were inevitable during the whole experiment and analysis.
Apart from the oxidation behavior of Inconel 617 caused by the dissolution of carbon dioxide, the carburization of Inconel 617 should also be considered \[8, 10\]. Considering the uncertainty of the EDS analysis, the GDOES analysis was used to characterize the carbon content from gas/oxide to the substrate of Inconel 617. The carbon content from gas/oxide to the near-surface of the substrate was much higher than that of the substrate, as shown in figure 5(a). Underneath the Cr$_2$O$_3$ and Al$_2$O$_3$ oxide scales, a small peak of high content of carbon was observed in figure 5(a), which was due to the reaction between the ingress carbon and the outward diffusion of Cr ion at the near-surface of Inconel 617. After 1000 h, the carbon content was slightly higher than that of Inconel 617 exposed to supercritical carbon dioxide for 250 h, as shown in figure 5(b). The penetrated depth of the carbon was larger due to the inward diffusion of carbon \[12, 18\]. What’s more, The carbon was detected at the oxide surface by the Raman analysis in figure 6. Lastly, we found that the oxygen content was higher than the carbon at the depth range from 0.2 μm to 0.8 μm, indicating that the internal oxidation of Inconel 617 suffered in supercritical carbon dioxide was more serious than the carburization of Inconel 617. The formation of carbides at the sub-surface of the substrate was found due to the reactions between ingress carbon and outward diffusion of metallic ions. This caused the high carbon content in the penetrated zone, as shown in figure 5(b).

Therefore, the corrosion process of Inconel 617 in supercritical carbon dioxide at 650 °C was composed of the outward diffusion of Cr and Al cations and the inward diffusion of O and C anions, leading to the oxidation and carburization of investigated materials, as shown in figure 4(a). The oxidation of Inconel 617 in an oxidizing atmosphere have been widely investigated \[21, 22\]. The oxidation products were mainly a thick Cr$_2$O$_3$ scale and some Cr–Al oxides along the grain boundaries \[22\]. However, in our result, underneath a thick Cr$_2$O$_3$ scale an amorphous Al$_2$O$_3$ scale replaced the Cr–Al oxides along the grain boundaries, this may be caused by the existence of the carbon at this position. Moreover, the carbon deposited at the surface of the oxide scale was also confirmed, which was caused by the reactions between metallic cations and carbon dioxide. Partial carbon penetrated through the oxidation scales into the substrate and reacted with the outward diffusion cations, forming carbides underneath the oxide scales, as shown in figure 5(b). This enriched the diffusion law of the carbon during the corrosion in supercritical carbon dioxide.

4. Conclusions

Corrosion behavior of Inconel 617 in supercritical carbon dioxide at 650 °C was reported in this article. The corrosion products formed on Inconel 617 were composed of a thick Cr$_2$O$_3$ layer, an amorphous Al$_2$O$_3$ layer and a carbon-penetrated zone from the gas/oxide scale interface to the substrate. Carbon was deposited on the oxide scales. Other carbon was penetrated into oxide scales, resulting in the formation of carbides at the sub-
surface of the substrate. The oxidation rate of Inconel 617 was much larger than the carburization rate in supercritical carbon dioxide environment.
Acknowledgments

This work is supported by Supported by State Key Lab of Advanced Metals and Materials (2019-Z05) National Natural Science Foundation of China (51806166), and the Innovative Talents Support Plan of China Postdoctoral Foundation (BX2019269).
ORCID iDs

Zhiyuan Liang  © https://orcid.org/0000-0003-3976-8714

References

[1] Feher E G 1968 Energy Convers. 8 85–90  
[2] Furukawa T and Rouillard F 2015 Prog. Nucl. Energ. 82 136–41  
[3] He L, Roman P, Leng B, Sridharan K, Anderson M and Allen T R 2014 Corros. Sci. 82 67–76  
[4] Firouzdor V, Sridharan K, Cao G, Anderson M and Allen T R 2013 Corros. Sci. 69 281–91  
[5] Nguyen T D, Zhang J Q and Young D J 2015 Mater. High Temp. 32 16–21  
[6] Nguyen T D, Zhang J and Young D J 2016 Corros. Sci. 112 110–27  
[7] Pint B A, Brese R G and Keiser J R 2017 Mater. Corros. 68 151–8  
[8] Rouillard F, Moine G, Tabarant M and Ruiz J C 2012 Oxid. Met. 77 57–70  
[9] Holcomb G R, Carney C and Doğan O N 2016 Corros. Sci. 109 22–35  
[10] Furukawa T, Inagaki Y and Aritomi M 2011 Prog. Nucl. Energ. 53 1050–5  
[11] Liang Z, Yu M, Gui Y and Zhao Q 2018 JOM-Int US 70 1464–70  
[12] Liang Z, Gui Y, Wang Y and Zhao Q 2019 Energy 175 345–52  
[13] Saunders S R J, Monteiro M and Rizzo F 2008 Prog. Mater. Sci. 53 775–837  
[14] Viswanathan R, Sarver J and Tanszosh J M 2006 J. Mater. Eng. Perform. 15 255–74  
[15] Pint B A and Keiser J R 2015 JOM-US 67 2615–20  
[16] Nguyen T D, Zhang J and Young D J 2014 Corros. Sci. 89 220–35  
[17] Young D J, Nguyen T D, Felter P, Zhang J and Cairney J M 2014 Scripta Mater. 77 29–32  
[18] Lee H J, Kim S H, Kim H and Jang C 2016 Appl. Surf. Sci. 388 483–90  
[19] Lee H J, Subramanian G O, Kim S H and Jang C 2016 Corros. Sci. 111 649–58  
[20] Liang Z, Singh P M, Zhao Q and Wang Y 2015 Oxid. Met. 84 291–305  
[21] Kim D, Jang C and Ryu W S 2009 Oxid. Met. 71 271–93  
[22] Liang Z, Wang Y and Zhao Q 2018 Metall. Mater. Trans. A 49 3133–44