Nuclear Engineering and Technology 48 (2016) 164–168

Available online at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Corrosion and Wear Properties of Cold Rolled 0.087% Gd Lean Duplex Stainless Steels for Neutron Absorbing Material

Yong Choi [a], *Youl Baik* [a], *Byung-Moon Moon* [b], *and Dong-Seong Sohn* [c,*]

[a] *Department of Materials Science and Engineering, Dankook University, Cheonan, Chungnam 330-714, South Korea*
[b] *Liquid Processing and Casting Technology R and D Group, Korea Institute of Industrial Technology, Incheon, 406-840, South Korea*
[c] *Nuclear Engineering Department, Ulsan National Institute of Science and Technology, Ulsan, 689-798, South Korea*

ARTICLE INFO

Article history:
Received 16 April 2015
Received in revised form
1 July 2015
Accepted 6 July 2015
Available online 31 October 2015

Keywords:
Corrosion
Duplex stainless steel
Gd neutron absorber
Mechanical property

ABSTRACT

Lean duplex stainless steels with 0.087 wt.% gadolinium (Gd) were inert arc-melted and cast in molds of size 10 mm × 10 mm × 20 mm. The micro-hardnesses of the rolling direction (RD), transverse direction (TD) and short transverse (ST) direction were 258.5 H_V, 292.3 H_V, and 314.7 H_V, respectively. A 33% cold rolled specimen had the crystallographic texture that (100) pole was mainly concentrated to the normal direction (ND) and (110) pole was concentrated in the center of ND and RD. The corrosion potential and corrosion rate in artificial seawater and 0.1M H_2SO_4 solution were in the range of 105.6–221.6 mV_{SHE}, 0.59 –1.06 mA/cm^2, and 4.75–8.25 mV_{SHE}, 0.69–1.68 mA/cm^2, respectively. The friction coefficient and wear loss of the 0.087 w/o Gd-lean duplex stainless steels in artificial seawater were about 67% and 65% lower than in air, whereas the wear efficiency was 22% higher. The corrosion and wear behaviors of the 0.087 w/o Gd-lean duplex stainless steels significantly depended on the Gd phases.

1. Introduction

More efficient storage of spent nuclear fuel is one of the most important issues in current Korean nuclear industry, since the amount of stored fuel will soon approach the full storage capacity. Most spent fuel storage racks use boron as the neutron absorber material, in forms of Boral, Metamic, or borated stainless steel, because of the high thermal neutron absorption cross section and ease of fabrication [1,2]. However, boron has been found to produce helium gas as it absorbs neutrons, which leads to the formation of He gas bubbles during its use in the spent fuel racks. This harms the integrity of the rack [3,4]. Recently, duplex stainless steel containing gadolinium (Gd) has been under development as a neutron-absorbing structural material for spent fuel racks [5]. Gd isotopes have a much higher thermal neutron absorption cross section (>60 times higher for Gd-157 than for B-10) and a higher isotopic abundance of the strong neutron absorber: 30.45% for thermal neutron absorption cross section > 60,000 barn (Gd-155, Gd-157) versus 19.9% for thermal neutron absorption cross

* *Corresponding author.*
E-mail address: dssohn@unist.ac.kr (D.-S. Sohn).

http://dx.doi.org/10.1016/j.net.2015.10.002

section = 3,840 barn (B-10). Therefore, it has a good potential for use as an absorber in the structural material, if dissolved in stainless steel.

Austenitic stainless steels have been used as the structural alloys for the transportation and storage of spent nuclear fuel. Recently, duplex stainless steels with austenitic and ferritic phases have been favorably considered as the structural material in various applications because of their higher strength and better corrosion resistance than a single phase of austenitic stainless steels. Various duplex stainless steels with different alloying elements, such as chromium, nickel, and molybdenum, have been developed [6]. Among these alloys, lean duplex stainless steels, which have little alloying elements, have been tried as the neutron-absorbing material, as they may cause less precipitation by neutron-induced phase transformation during usage [7].

Although duplex stainless steels have been widely studied, little information is available on the effects of neutron-absorbing elements on the microstructure development and the characteristics of lean duplex stainless steels. Hence, the objective of this study is to fabricate a lean duplex stainless steel with Gd and to characterize its mechanical and corrosion behaviors.

2. Materials and methods

The lean duplex stainless steels with Gd were fabricated by using plasma arc melting (PAM-Plasma, Japan), mother alloys of Fe–Mo, Fe–Gd, and Fe–Cr–Ni alloys, and alloy elements such as manganese (Mn > 99.99, Samchang, Korea) and silicon (Si > 99.99, Samchang). The mother alloys were prepared by vacuum induction melting (Inductotherm, USA) with metallic slots of iron (Fe > 99.99, Samchang), chromium (Cr > 99.99, Samchang), nickel (Ni > 99.99, Samchang) and Gd (Gd > 99.9%, Samchang).

The melt was poured at 1,640°C into an alumina mold coated with yttria (Y_2O_3). The cast block, with dimensions of 150 mm × 75 mm × 15 mm, was cut and hot rolling was carried out three times at 950°C, solution treatment at 1,070°C for 1 hour, and water-quenching; finally, cold rolling was carried out to a thickness of 3.0 mm.

Table 1 is the final composition of the final product, as determined by inductively coupled plasma mass spectrometry (Agilent-8800, Agilent Technology, USA).

The microstructure of the specimen was observed by optical microscopy (AT Microscope, MX-3000, Korea) after etching with Carpenter's etchant. The crystallographic texture was determined by electron backscattered diffractometry (Jeol, JSM-7100F, Japan).

Microhardness was determined with a micro-Vickers hardness tester (HuaTec, DHV-1000, China) at a load of 98 N for rolling directions, like rolling direction (RD), transverse direction (TD), and short transverse (ST) direction. Mechanical properties such as ultimate tensile strength, yield strength, and elongation were determined with a universal test machine (Shimadzu, AG-300kNX, Japan). The specimen was prepared by ASTM A370. Wear resistance was measured with a pin on disk type wear tester (R&B, Triboss PD-102, Korea) and the wear surface and wear debris were observed and analyzed by scanning electron microscopy (Coxem, CX200-TA, Korea) and energy dispersive spectroscopy (Hitachi, S-4300, Japan). Corrosion behavior in an artificial seawater (ASTM D1141-98) and 0.1M H_2SO_4 solution was measured by the potentiodynamic method (Potentiostat, Gamry 100, USA) using reference and counter electrodes of saturated calomel electrode (Princeton, USA) and platinum rod.

Table 1 – Chemical composition of cast lean duplex stainless steel (wt.%).

Fe	Cr	Ni	Mo	Si	Mn	Gd
Balance	22.25	5.33	2.90	0.45	0.85	0.087

3. Results and discussion

3.1. *Microstructure observation and crystallographic texture analysis*

Fig. 1 is the microstructure of the 0.087% Gd lean duplex stainless steel in which the elongated austenitic and ferritic phases were well observed. Average sizes of the grains on the surface normal to the ST, TD, and RD directions were ⊥ST = 6.58, ⊥TD = 6.55, and ⊥RD = 10.66 μm.

Fig. 2 is the typical crystallographic texture of the 33% cold rolled 0.087% Gd lean duplex stainless steel. As shown in Fig. 2, mainly (100) pole was concentrated to sample the normal direction (ND) which was parallel to the ST direction (ND//⊥ST) and (110) pole was concentrated in the middle of the ND and the RD.

3.2. *Mechanical properties and corrosion behavior*

The micro-Vickers hardnesses of the RD, TD, and ST direction were 258.5 H_V, 292.3 H_V, and 314.7 H_V, respectively. Ultimate tensile strength, yield strength, and elongation were 694 MPa, 538 MPa, and 37.1%, respectively. This data means that mechanical properties of the 0.087% lean duplex stainless steels are much higher than those of the commercial neutron absorber materials such as boron stainless steels (ASTM-A887-89 Grades A and B).

Fig. 3 shows the polarization curves of the 0.087% Gd lean duplex stainless steels in an artificial seawater and 0.1M H_2SO_4 solution at 25°C. As shown in Fig. 3, passivity was not present in both solutions. Table 2 shows the corrosion potential and corrosion rate in the artificial seawater and 0.1M H_2SO_4 solution. The corrosion rates of the 0.087% Gd lean duplex stainless steels were much higher in 0.1M H_2SO_4 solution than in artificial seawater. The corrosion potential and corrosion rate in artificial seawater and 0.1M H_2SO_4 solution were in the range of 105.6–221.6 mV_{SHE}, 0.59–1.06 mA/cm^2, and 4.75–8.25 mV_{SHE}, 0.69–1.68 mA/cm^2, respectively. The corrosion rate depended on the cold rolling direction, increasing in the order of surface normal to the ST direction, TD, and RD. As shown in Figs. 1 and 2, the average grain sizes of the surface normal to the ST direction, TD and RD were ⊥ST = 6.58, ⊥TD = 6.55, and ⊥RD = 10.66 μm, respectively, where grains had the preferred orientation of mainly (100) pole parallel to the ST direction (ND//⊥ST). This means that the corrosion rate significantly depended on the grain boundary density and crystallographic orientation. This was in good agreement with previous results [6].

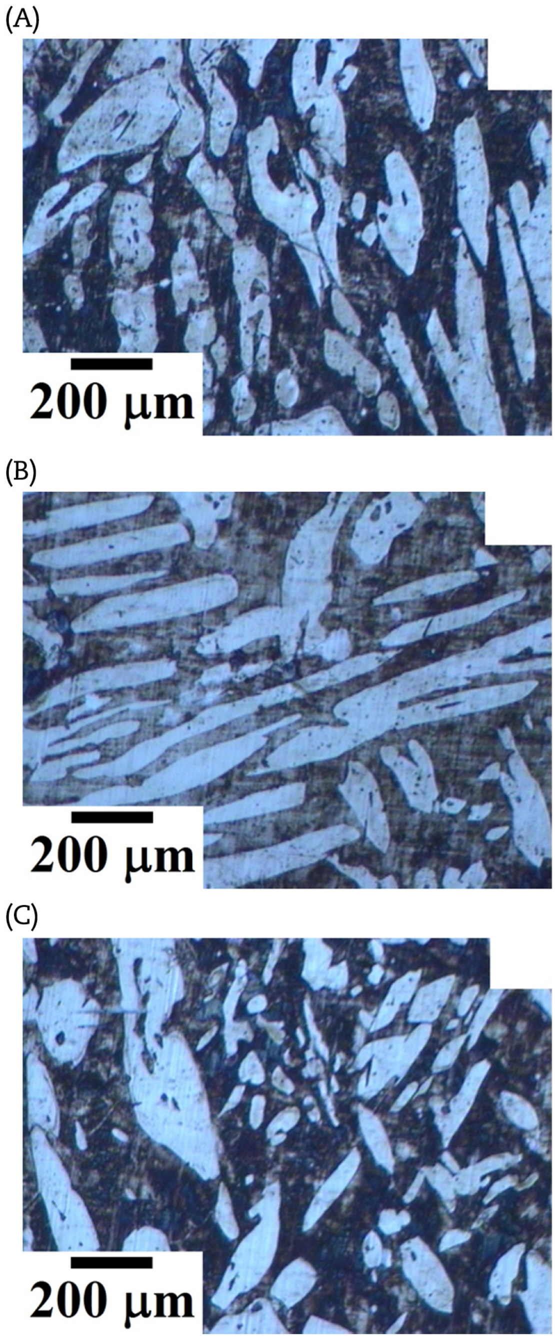

Fig. 1 – Microstructure of the 0.087% Gd lean duplex stainless steel with cold rolling directions: surface normal to (A) short transverse (ST) direction, (B) transverse direction (TD), and (C) rolling direction (RD).

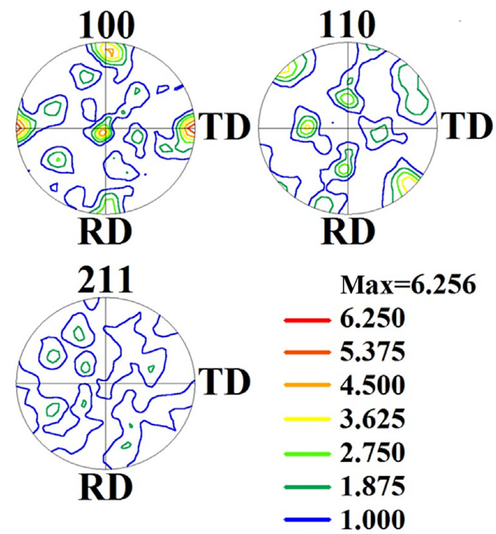

Fig. 2 – Typical crystallographic texture of 100, 110, and 211 poles.

3.3. *Wear behavior*

Table 3 shows the friction coefficient, wear loss, and wear efficiency of the 0.087% Gd lean duplex stainless steels in air and artificial seawater. The friction coefficient and wear loss of the 0.087% Gd lean duplex stainless steels in artificial seawater were about 67% lower and 65% lower, respectively, than in air, whereas the wear efficiency was 22% higher.

In order to study the wear behaviors with wear environment, the worn surface and the wear debris were observed and analyzed by scanning electron microscopy and energy dispersive spectroscopy, respectively. Fig. 4 shows typical scanning electron microscopy images of the worn surfaces in air and artificial seawater. A relatively rough surface caused by friction wear was observed. The average debris sizes of the worn surfaces in air and in artificial seawater were 4.02 μm and 3.04 μm, respectively.

Table 4 is the chemical composition of the wear debris. Comparing Table 1 of the chemical composition to the matrix alloys, the wear debris had a much greater amount of Gd and a little Mn. This indicates that the phases with Gd and Mn were preferentially worn during the pin-on disk type friction wear test. The main phases of Gd and Mn in the duplex stainless steels are Gd–Fe intermetallics and MnS phases. Especially, the artificial seawater increased the wear efficiency by about 18% and decreased the size of wear debris by about 24%.

Since passivity was not observed in the artificial seawater, as shown in Fig. 3 of polarization curves, the wear increased efficiency in the artificial seawater was significantly affected by corrosion of the phases with Gd. Hence, the corrosion and wear behaviors of the 0.087% Gd lean duplex stainless steels significantly depended on the Gd phases.

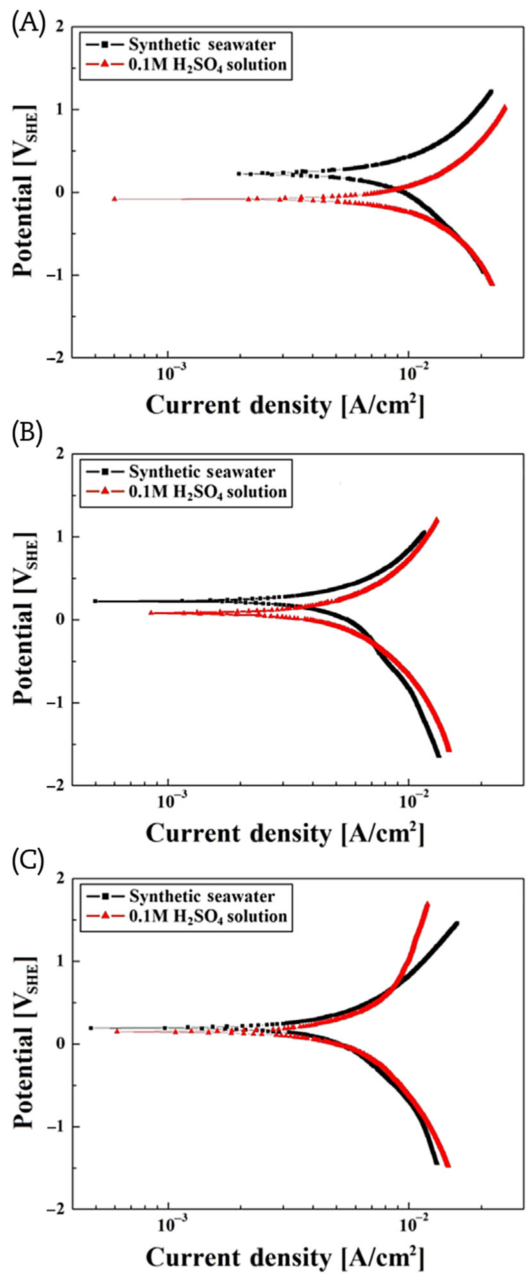

Fig. 3 – Typical polarization curves of 0.087% Gd-lean duplex stainless steels in an artificial sea water and 0.1 M H_2SO_4 solution at 25°C with cold rolling directions. Surface normal to (A) rolling direction (RD), (B) transverse direction (TD), and (C) short transverse (ST) direction.

Table 2 – Corrosion potential and corrosion rate in artificial seawater and 0.1M H_2SO_4 solution.

Solution	Artificial sea water (pH = 6)			0.1M H_2SO_4 (pH = 1)		
Surface	⊥RD	⊥TD	⊥ST	⊥RD	⊥TD	⊥ST
E_{corr} [mV_{SHE}]	221.6	221.0	105.6	8.25	8.17	4.75
I_{corr} [mA/cm^2]	1.06	0.77	0.59	1.68	0.92	0.69

Table 3 – Friction coefficient, wear loss, and wear efficiency of the 0.087% Gd lean duplex stainless steels in air and artificial sea water.

	Friction coefficient	Wear loss	Wear efficiency
Air	6.286	0.113	0.018
Artificial sea water	2.044	0.039	0.022

4. Conclusion

(1) The 33% cold rolled 0.087% Gd lean duplex stainless steels had average grain sizes of the grains of t on the surface normal to the ST direction, TD, and RD of 6.58 μm, 6.55 μm, and 10.66 μm, respectively. The specimen had the crystallographic orientation with mainly (100) pole concentrated parallel to the ST direction (ND//⊥ST) and (110) pole concentrated in the middle of the ND and the RD; (2) the micro-Vickers hardnesses of the 33% cold rolled 0.087% Gd lean duplex stainless steels with RD, TD, and ST direction were 258.5 H_V, 292.3 H_V, and 314.7 H_V, respectively. Ultimate tensile strength, yield strength, and elongation were 694 MPa, 538 MPa, and 37.1%, respectively; (3) the corrosion potential and corrosion rate in artificial seawater and 0.1M H_2SO_4 solution were in the range 105.6–221.6 mV_{SHE}, 0.59–1.06 mA/cm^2, and 4.75–8.25 mV_{SHE},

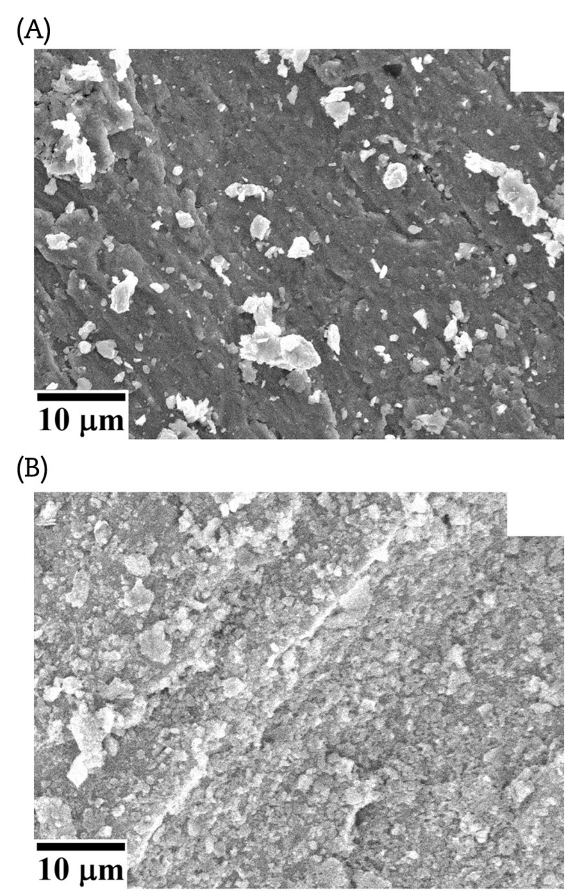

Fig. 4 – Typical scanning electron microscopy images of the worn surfaces. (A) Air and (B) artificial seawater.

Table 4 – Chemical composition of wear debris with wear environment.

Elements	Fe	Cr	Ni	Mo	Gd	Mn	Si	O
Air	63.91	18.61	2.82	2.67	2.12	1.67	1.11	7.10
Artificial sea water	62.53	19.61	3.13	2.13	2.34	2.39	0.87	6.99

0.69–1.68 mA/cm^2, respectively. The corrosion rate depended on the cold rolling direction, increasing in the order of the surface normal to the ST direction, TD, and RD. The passivity was not present in both solutions; and (4) the friction coefficient and wear loss of the 0.087% Gd lean duplex stainless steels in artificial seawater were about 67% lower and 65% lower, respectively, than in air, while the wear efficiency was 22% higher. The phases with Gd and Mn were preferentially worn during the pin-on disk type friction wear test. The corrosion and wear behaviors of the 0.087%Gd lean duplex stainless steels significantly depended on the Gd phases.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgments

This work was supported by the Nuclear Power Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resources from the Ministry of Trade, Industry & Energy, Korea (Number 20131520000060).

REFERENCES

[1] A. Machiels, R. Lambert, Handbook of Neutron Absorber Materials for Spent Nuclear Fuel Transportation and Storage Applications, 2009-ed 1019110, Electronic Power Research Institute, 2009.

[2] American Society for Testing and Materials (ASTM) A 887-89, Standard Specification for Borated Stainless Steel Plate, Sheet, and Strip for Nuclear Application, ASTM, West Conshohocken (PA), 2004.

[3] G.W. Wachs, J.W. Sterbentz, L.M. Montierth, F.K. Tovesson, T.S. Hill, Characterization of an Advanced Gadolinium Neutron Absorber Alloy by Means of Neutron Transmission, INL/CON-07–12838, Idaho National Laboratory, Idaho Falls (ID), 2007.

[4] G.W. Wachs, J.W. Sterbentz, et al., Nickel Based Gadolinium Alloy for Neutron Adsorption Application in Ram Package, PATRAM 2007, Miami (FL), Oct. 2007.

[5] Y. Choi, B-M. Moon, D-S. Sohn, Fabrication of Gd containing duplex stainless steel sheet for neutron absorbing structural materials, Nucl. Eng. Technol. 25 (2013) 689–694.

[6] L. Karlsson, H. Norden, Non-equilibrium grain boundary segregation of boron in austenitic stainless steel II. Fine scale segregation behavior, Acta Metall. 36 (1988) 13–24.

[7] X. Tang, Sigma phase characterization in AISI 316 stainless steel, Microsc. Microanal. 11 (2005) 78–79.