

EFFECT OF OXIDE ON SOLID PARTICLE EROSION BEHAVIOR OF AISI 410 MARTENSITIC STAINLESS STEEL

Watcharapong Rungphetwong¹, Mack Boonpensin¹, Piyorose Promdirek^{1,*} and Pornsak Thasanaraphan²

Received: August 21, 2020; Revised: January 20, 2021; Accepted: January 26, 2021

Abstract

The objective of this research is to study the effect of oxide scale on the solid particles erosion behavior of AISI 410 martensitic stainless steel (12%Cr, 0.15%C) which was used as a wearing plate in the Coal-fired Power plant due to high strength and oxidation resistance properties. Solid particle erosion tests were investigated with several parameters such as velocities and impact angles for bare and oxidized samples. The erosion behavior of oxidized samples with the simulated atmosphere (1%SO₂, 20%H₂O, 20%CO₂, 10%O₂, N₂%) at 600°C for 100 h was compared with bare samples at room temperature. The results showed that the oxide led to a decreasing erosion rate for all impact velocities. Moreover, the surface morphology was finally examined by SEM. The erosion behavior of MSS was further discussed in this research.

Keywords: Solid Particle Erosion, Martensitic, AISI 410, Oxidation

Introduction

In the power plant industry there is a lot of waste energy, such as thermal energy which can be reused to save energy in the production process. The economizer is an equipment which receives heat energy from hot flue gas before moving out from firebox and into the stack during the boiler process to preheat a feed water. The waste of thermal energy can be economized by this equipment in order to increase the water temperature in the process (Oakey, 2011). Almost problems found in the economizer area are mostly caused by erosion, and temperature high oxidation. Moreover, high

temperature oxidation in power plants usually occurs under combustion gas atmosphere which consists of various types of gas such as CO₂, O₂, H₂O, SO₂, and N₂. (Baz *et al.*, 2017) carried out a study of high-temperature corrosion of tube between low Cr-tube and high Cr-tube under the flue gas at 650°C. It has been found that the protective layer of Cr₂O₃ under the oxy-firing oxidation atmosphere which is growth and broken down under the combustion atmosphere. Damage resulting in corrosion and erosion reduced the lifetime of the equipment, directly affecting the

¹ Department of Materials and production technology engineering, Faculty of engineering, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand. Tel. 02-555-2000; Fax 02-587-4335. E-mail: watcharapong.rpw@hotmail.com

² Material Properties Analysis and Development Centre, Thailand Institute of Scientific and Technological Research, Pathumthani, Thailand. E-mail: piyorose.p@eng.kmutnb.ac.th

* Corresponding author

continuation of the production process. The most erosion problematic type of the economizer that is the solid particle erosion.

Solid particle erosion (SPE) is the continuation of mass loss that causes by repeated impact of solid particles on the material surface. As well known, the eroded surface of materials was reported by erosion rate. The parameters for erosion rate were studied in several literatures. The impact angle and particle velocity were important parameter. The results showed that the erosion rate has increased with increasing impact angle up to 40° and decreasing until 90° (Nguyen *et al.*, 2014) for ductile behavior damage. In different particle velocity, the mass loss increased with increasing velocity of particle from 20 m/s to 80 m/s for sand blast erosion tests (Paul and Mohamed, 2014). A number of power plants have protected the initial problem by using the wearing plate equipment, which is a shell that can be applied to the tube surface. Therefore, assessing the damage caused by the operation that leads to prevention is necessary in order to increase the life time as well as reduce the unplanned shutdown in the production processes. In the power plant industries, Martensitic stainless steel is suitable and popular to use as a wearing plate.

Martensitic stainless steels (MSS) are ternary alloys of iron, chromium, and carbon. They are hardenable by heat treatment resulting in high surface hardness and high wear resistance. For mechanical-chemical action, martensitic stainless steels are usually applied for their oxidation or corrosion resistance. While there are many modifications of the MSS, the AISI 410/410 alloy (0.15%C, 11.5-13%Cr) is the most widely used commercial grade. Garrison and Amuda (2017) Because it is contained by low chromium and alloying elements, so it is more cost effective than the other grades. Kim and Park (1998) studied the SPE behavior of AISI 403 MSS, and Trilok *et al.* (1991) carried out a study of SPE test with silicon carbide particle on AISI 410 MSS at impact angle of 30°, 60°, and 90°. From those MSS research, SEM examination of the eroded surfaces showed the evidences of the plastic deformation. It was concluded that the erosion behavior of AISI 403 and 410 MSS occurred in a ductile behavior. However, There are not investigated the effect of the oxide scale on SPE behavior in the past works.

In the present study, the high temperature oxidation or erosion behavior may be affected by the SPE. Especially, the thickness of oxide scale related to the erosion behavior were intensively studied. The objective of this research is therefore to study the effect of solid particle on the erosion behavior of the oxide scale of AISI 410 stainless steel when it is

used as a wearing plate in the Coal-fired Power plant at 600°C.

Materials and Methods

Martensitic stainless steel grade AISI 410 was used for SPE testing. The chemical composition of AISI410 was examined by emission spectrometer (METEK LAB LAVM10) as shown in Table 1.

Table 1. Chemical composition of AISI 410

	Chemical Composition (wt. %)							
	Fe	Cr	Mn	C	Si	Ni	P	S
AISI 410	Bal.	12.00	1.00	0.15	0.50	0.07	0.02	0.01

The 4 mm thick AISI410 steels were cut into a square shape with dimension of 15×15 mm². All samples were ground with SiC sandpaper until 1,200 grit and then cleaned by ultrasonic agitation, finally dried in air. In order to prepare the oxidized samples, the samples were conducted in the simulated atmosphere for the exposure time of 1, 25, and 100 h at temperature of 600°C and naturally cooled in horizontal furnace. The simulated atmosphere was composed of a mix of several different gases as shown in Table 2, according to the simulation of combustion gas of previous study (Baz *et al.*, 2017). For the preparation of 20%v/v water vapor and nitrogen gas mixture, The nitrogen was flowed into the water bottle heated to the temperature of 59.4°C according to the Clausius- Clapeyron equation (Gaskell and Laughlin, 2017) from thermodynamic data-compiled by Barin (Barin, 1989). Air in the furnace chamber was eliminated by the gas mixture with the volumetric flow rates of 0.5 L/min for 30 min.

Table 2. Composition of the simulated atmosphere for oxidation atmosphere

	Gas composition (%v/v)				
	N ₂	O ₂	CO ₂	H ₂ O	SO ₂
Oxidation atmosphere	49	10	20	20	1

All samples were performed by using an apparatus based on (ASTM G76, 2018) standard testing for SPE testing. Due to the similar thickness of oxide scale in the service of power plant, the oxidation of samples for 100 h was selected. The bare samples and oxidized samples were then tested by the sand blast machine at room temperature. Silicon carbide (SiC) was used as the abrasive particle with an angular shape as revealed

in Figure 1. For SPE testing, an amount of silicon carbide was fixed in 50 g. The radius of particle size was approximately used in the range of 70-85 μm . The impact angles of 30°, 45°, 60°, and 90° were carried out for the test. The particle velocity can be assumed that air and sand particle velocity are almost identical. Particle velocities can be calculated by flow rate of air, showing 23, 34, and 47 m/s.



Figure 1. Morphology of the angular silicon carbide particle by SEM

The distance from the nozzle to the sample surface was equal to 5 mm. The samples were weighed by using microbalance with accuracy of ± 0.00001 before and after testing. Erosion rate were calculated by the weight loss of the target per weight of impact particle ($\mu\text{g/g}$). The erosion test was repeated at least 2 times in each condition.

For achieving high quality of cross-section image, the preparation of the oxidized specimen should be carefully considered. Cold mounting metallographic techniques were used for scanning electron microscope. The process was done by low-speed grinding with 80 to 1,200 grit of sandpaper and polishing with colloidal alumina suspension. And the optical microscope (OM, ECLIPSE MA200) were used for observing the interface between the oxide and metal substrate before Scanning electron microscope examination. The cross-section image and the morphology of eroded surface were analysed by Scanning Electron Microscope (SEM, JOEL JSM-6610LV) for the mode of backscatter electrons and Scanning Electron Microscope (SEM, Thermo Scientific PrismaE) for the mode of secondary electron image. An X-ray Diffraction (XRD, BRUKERD8 ADVANCE) was performed for phase identification by using with $\text{Cu K}\alpha$ radiation.

Results and Discussion

Figure 2 shows the plot of the mass gain versus time during oxidation at 1, 25, and 100 h. The result indicated that the corrosion kinetics at 600°C was the parabolic law, following the general oxidation of metal in air or oxygen (Young, 2016).

$$\left(\frac{\Delta m}{A}\right)^2 = k_p t \quad (1)$$

where $(\Delta m)/A$ is the mass gain (g/mm^2), t is the oxidizing time (hour) and k_p is the parabolic rate constant. The same results were contributed by (Viswanathan *et al.*, 2007). They showed that the parabolic law can obtain on the oxidized AISI 410 MSS in air atmosphere at elevated temperature.

According to the macro examination result, the surface color of bare and oxidized samples was significantly different, showing the dark gray and metallic color for oxidized and bare samples respectively. The physico-chemical characteristics of the oxide scale were investigated by SEM in the mode of backscatter electrons equipped. The slightly thin oxide scales for 100 h was found on the surface of oxidized sample with approximate thickness of 1.3 μm (Figure 3). The ImageJ software was used to examine the thickness of oxide scale. To identify oxide phase on the substrate, the XRD technique was applied on the surface of the sample giving the pattern as shown in Figure 4. The result shows the presence of Cr_2O_3 peak, leading to the possible Cr_2O_3 scale. Figure 5 presented the comparison graph of the erosion rate versus impact angle between bare and oxidized samples. It seem that the erosion rate decreased with increasing of impact angle for all velocities. The relationship of the erosion rate and impact angle was linear.

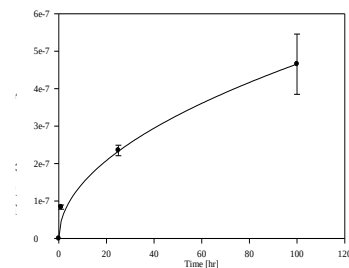


Figure 2. The graph of oxidized samples between mass gain and time

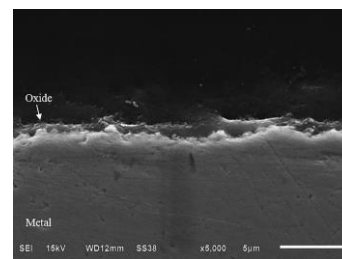


Figure 3. The cross section of oxide scale on the sample oxidized at 600°C for 100 h

The highest erosion rate occurred at the impact angle of 30° for both samples, showing the surface damage by shear. The erosion rate of the oxidized samples was typically lower than that of the bare samples for all impact velocities. In addition, the erosion rate of all samples increased with the increased impact velocity. Considering the value of slope in Table 3, the slope trend to increase with increasing of impact velocity. The higher impact velocity affects on the slope of erosion rate. This result is consistent with the result of other research (Huttunen-Saarivirta *et al.*, 2011). They proposed that the mass loss for metal increased as the particle or impact velocities increased as a result of the impact forces and kinetic energy that impinged at the surface of the sample become higher enough to cause of higher removal of metal. Figure 6 shows the comparison graph of mass loss versus impact

Table 3. The slope of the mass loss as a function of impact angle on bare and oxidized sample in variable particle velocities

Velocity (m/s)	Sample	Slope	R ²
23	Bare	0.3291	0.9698
	Oxidized	0.2514	0.9878
34	Bare	0.6644	0.8820
	Oxidized	0.6400	0.9557
47	Bare	1.2568	0.9883
	Oxidized	1.1798	0.9549

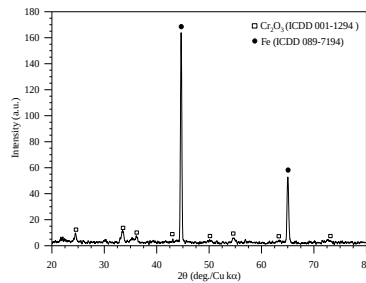


Figure 4. XRD Pattern of the AISI 410 after oxidized at 600°C for 100 h

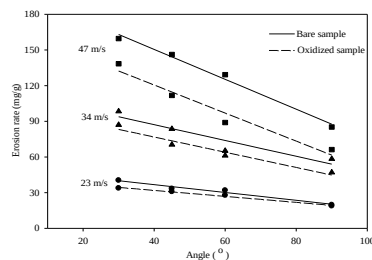


Figure 5. Comparison of the erosion rate and impact angles between bare samples and oxidized samples at 100 h

velocity. It seemed that the erosion rate was linear function for all of the particle impact angle.

The surface morphology of eroded surface of the bare sample at impact angle of 30° and 90° were exhibited by SEM in the mode of secondary electron image as shown in Figure 7(a) and 7(b). Due to the sliding abrasion at low impact angle as shown in Figure 7(a), erodent surface exhibited scratching or

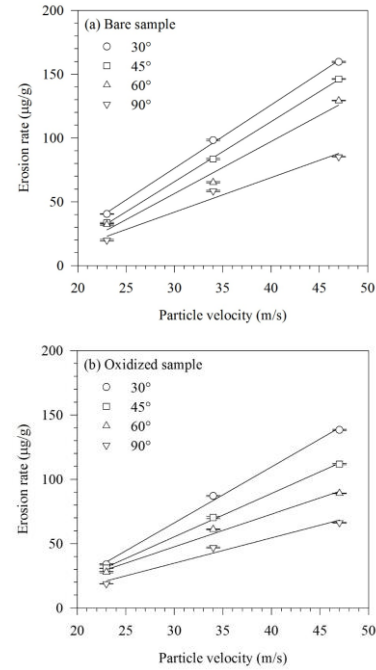


Figure 6. The comparison graph of overall mass loss versus velocity, (a) bare sample, (b) oxidized samples at 100 h

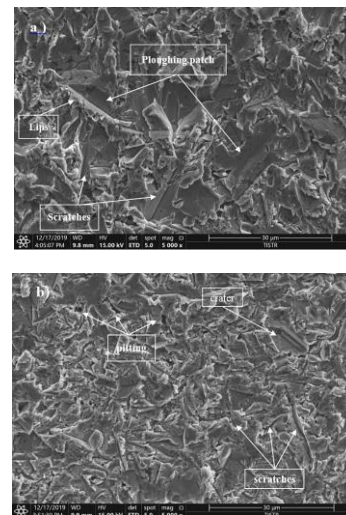


Figure 7. The erosion damage of bare samples, (a) 30° , (b) 90°

grooving and ploughing path with lips at the side. In addition, the erosion damage at 90° (Figure 7(b)) displayed a crater, pitting at random position. In some areas, a scratching action was also observed. It was possible to observe the embedded particle in the craters due to the steep impact angle. The bare samples almost presence the plastic deformation on the erosion surface. Moreover, the surface morphology of the eroded surface of the oxidized sample at impact angle of 30° and 90° were exhibited by SEM as shown in Figure 8(a) and 8(b). In the lower impact angle (Figure 8(a)) shows a cutting or sliding action on the surface such as ploughing action with lips and scratching. The Figure 8(b) showed a crater, a pitting actions, and scratching actions at random locations. As mentioned above, all samples were essentially damaged by plastic deformation. The main wear mechanism was the ductile fracture.

According to the results as mention above, AISI 410 had a ductile erosion behavior because these materials showed a higher erosion rate at 30°. In the other hand, the brittle type of erosion behavior will present the higher erosion rate at 90° of impact angle. In addition, the ductile behavior was seen by the evidence of the plastic deformation at the surface of materials. The conclusion is based on other literature review (Hutchings, 1992). In addition, other researches showed the same SPE behavior of MSS at room temperature (Laguna-Camacho *et al.*, 2013; Vite-Torres *et al.*, 2013). AISI 410 with oxide scale showed the higher performance of erosion resistance than that of the bare sample of AISI 410. (Sundarajan and Manich, 1997), and later (Wellman and Nicholls, 2004) proposed model of strong interaction between oxidation and erosion behavior based on substrate and oxide properties. They reported that the parameter of the model following the ratio between the oxide thickness (z) and radius of particle size (a) (z/a). The criteria conditions of relative thickness are three cases. When the z/a ratio is less than 0.1 ($z/a < 0.1$), the relative thickness of oxide film is low. Under this condition the oxide properties are not important for the SPE behavior, it is controlled by the substrate properties (Substrate mode or substrate dominated erosion). For $z/a > 0.1$, this case is called that scale modified by the SPE behavior is contributed in the rate of oxide scale growth and rate of removal of oxide/some surface of substrate. Last case $z/a > 1.0$, the thickness of oxide scale increased and assuming oxide scale/ substrate interface was good adhesion. The oxide properties have a major effect on the SPE behavior. Thus the oxide scale is able to accommodate the damage from the impact of particle. Only oxide scale is removed during the SPE test, resulting in no damage to the

substrate. The SPE behavior is controlled by oxide properties (Scale dominated mode). In this research, at $z/a = 0.016$ the thickness of oxide and radius of particle size is 1.3 μm and 70-85 μm , respectively. The new oxide cannot form on the eroded surface during the SPE test, hence the ratio is less than 0.1 ($z/a < 0.1$). The erosion behavior controlled by substrate mode is operative. Thus the oxide thickness is not sufficient for protecting the entire of metal substrate. The erosion-oxidation control by the substrate as shown in Figure 9. In these figures, the metal substrate under thin oxide was impacted by SPE testing. The thin oxide gave some protection for first impact. After that, the thin oxide has been removed whereas substrate metal being eroded cause by SPE testing. As expected in power plant service, the erosion will continue to damage on the oxidized surface all the time. There is no sufficient time to form the enough thickness of oxide scale into scale dominated mode ($z/a > 1.0$). So only thin oxide scale can form during the erosion damage, showing the surface damage with low of z/a ratio mode ($z/a < 0.1$).

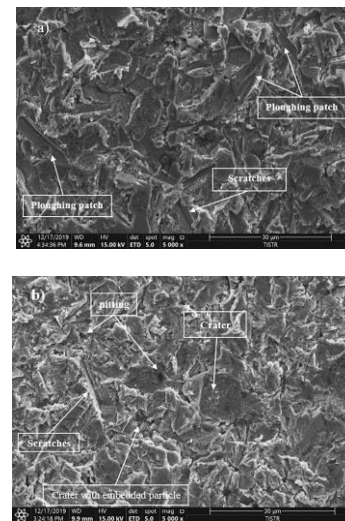


Figure 8. The erosion damage of 100 hour of oxidized samples, (a) 30°, (b) 90°

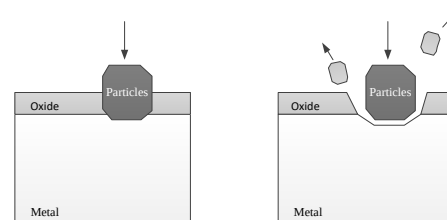


Figure 9. Schematic which illustrate the oxide-erosion control by substrate phenomena

Conclusions

The SPE behavior of the bare sample and the oxidized sample of AISI 410 MSS at room temperature was investigated. The following conclusions can be drawn.

1. The oxidized and the bare sample of AISI 410 MSS exhibited a ductile erosion behavior with maximum erosion rate at 30° of impact angle investigated by SEM.
2. The erosion rates for oxidized and bare samples increased with decreasing of impact angle. On the other hand, they increased with increasing of impact velocity.
3. The erosion rate of all angles increased with increasing particles velocity due to the high kinetic energy of the impingement particles.
4. The erosion behavior of oxidized metal can also be influenced by the value of oxide thickness and property. In this case, the oxide thickness is not sufficient to protect the metal substrate from the erosion, thus the behavior of oxidized metal is control by the metal substrate behavior.

Acknowledgments

The authors would like to thanks to Thailand institute of scientific and technological research for The Master Scholarship. Moreover, Department of Materials and Production Technology Engineering of King Mongkut's University of Technology North Bangkok are acknowledged for the Research instrument support to authors.

References

- ASTM G76. (2018). Standard Test method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets. ASTM International, PA, USA.
- Barin, I. (1989). Thermodynamical Data Pure Substances. VCH, Germany, 1,739p.
- Baz, I.J., Juan C., Etschmann, B., Ninomiya, Y., and Lian, Z. (2017). High temperature tube corrosion upon the interaction with victorian brown coal fly ash under oxy-fuel combustion condition. *Proc. Combust. Inst.*, 36(3): 3941-3948
- Garrison, W.M. and Amuda, M.O.H. (2017). Stainless steels: martensitic. Reference Module in Materials Science and Materials Engineering, Elsevier Inc., The Netherlands, 9p.
- Gaskell, D.R. and Laughlin, D.E. (2017). Introduction to the Thermodynamics of Materials. 6th ed., CRC Press LLC, Boca Raton, USA, 714p.
- Hutchings, I. (1992). Friction and Wear of Engineering. 1st ed. Butterworth-Heinemann, Cambridge, UK, 280p.
- Huttunen-Saarivirta, E., Antonov, M., Veinthal, R., Tuiremo, J., Makela, K., and Siitonen, P. (2011). Influence of particle impact conditions and temperature on erosion-oxidation of steels at elevated temperatures. *Wear.*, 272(1):159-175.
- Kim, J.J. and Park, S.K. (1998). Solid particle erosion of AISI 403 stainless steel. *J. Mater. Sci. Lett.*, p. 1,503-1,506.
- Laguna-Camacho, J.R., Marquima-Chavez, A., Mendez-Mendez, J.V., Vite-Torres, M., and Gallado-Hernandez, E.A. (2013). Solid particle erosion of AISI 304, 316 and 420 stainless steel. *Wear.*, 301(1-2):398-405.
- Nguyen, Q.B., Nguyen, V.B., Lim, C.Y.H., Trinh, Q.T., Sankaranarayanan, S., Zhang, Y.W., and Gupta, M. (2014). Effect of impact angle and testing time on erosion of stainless steel at higher velocities. *Wear.*, 321:87-93.
- Oakey, J.E. (2011). Power plant life management and performance I improvement. 1st ed. Wood head Public limited, UK, 704p.
- Paul, O.C. and Mohamed, A.M.A. (2014). Erosion mechanism of API X42 and AISI 1018 Steel materials at Normal impact angle. *Int. J. Eng. Sci. Innov. Technol.*, 3(5):402-407.
- Sundarajan, G. and Manich, R. (1997). Solid particle erosion behavior of metallic materials at room and elevated temperatures. *Tribol Int.*, 30(5):339-359.
- Trilok, S., Tiwar, S.N., and Sundarajan, G. (1991). Room temperature erosion behavior of 304, 316 and 410 stainless steel. *Wear.*, 145:77-100.
- Viswanathan, V., Filmalter, R., Patil, S., Deshpande, S., and Seal, S. (2007). High-temperature oxidation behavior of solution precursor plasma sprayed nanoceria coating on martensitic steels. *J. Am. Ceram. Soc.*, 90(3):870-877.
- Vite-Torres, M., Laguna-Camacho, J.R., Baldenebro-Castillo, R.E., Gallardo-Hernandez, E.A., Vera-Cardenas, E.E., and Vite-Torres, J. (2013). Study of solid particle erosion on AISI 420 stainless steel using angular silicon carbide and steel round grit particles. *Wear.*, 301(1-2):383-389.
- Wellman, R.G. and Nicholls, J.R. (2004). High temperature Erosion-oxidation mechanism, maps and models. *Wear.*, 256(9-10):907-913.
- Young, D. (2016). High temperature Oxidation and Corrosion of Metals. 2nd ed. Elsevier, The Netherlands. 758p.