Indonesian Journal of Science & Technology

Journal homepage: http://ejournal.upi.edu/index.php/ijost/

High Temperature Oxidation Behavior of T91 Steel in Dry and Humid Condition

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ABSTRACT

High temperature oxidation behavior of T91 ferritic/martensitic steel was examined over the temperature range of 500 to 700°C in dry and humid environments. The weight gain result revealed that oxidation occurs at all range of temperatures and its rate is accelerated by increasing the temperature. The weight gain of the oxidized steel at 700°C in steam condition was six times bigger than the dry oxidation.. SEM/EDX of the cross-sectional image showed that under dry condition, a protective and steady growth of the chromium oxide (Cr_2O_3) layer was formed on the steel with the thickness of 2.39±0.34 μm. Meanwhile for the humid environment, it is found that the iron oxide layer, which consists of the hematite (Fe_2O_3) and magnetite (Fe_3O_4) was formed as the outer scale, and spinnel as inner scale. This result indicated that the oxidation behavior of T91 steel was affected by its oxidation environment. The existence of water vapor in steam condition may prevent the formation of chromium oxide as protective layer.

ARTICLE INFO

Article History:
Submitted/Received 10 May 2016
First Revised 07 Jun 2016
Accepted 30 Jun 2016
First Available online 09 Aug 2016
Publication Date 01 Sep 2016

Keyword:
High temperature oxidation
T91 steel,
Dry and steam condition,
Protective oxide.

1. INTRODUCTION

The environmental impacts of the burning fossil fuel are concerned by the world organization and international agencies. The combustion of coal has been contributed on the increased level of the carbon dioxide in atmosphere, which may result in the global warming (see http://www.ucsusa.org/clean_energy/coalvswind/c02c.html). To reduce the carbon dioxide emission, it is necessary for increasing the efficiency of energy production. However, the efficiency of the power plant is depending on the pressure and temperature of the live steam. (Skorek-Osikowska *et al.*, 2013) The thermal efficiency was referred to the parameter of Carnot thermodynamic cycle, in which it is an efficient heat-to-electricity conversion cycle. (Shengjun *et al.*, 2011) The higher efficiency of the system also can be obtained by increasing the temperature of the furnace or decreasing the temperature of the cooling fluid.(Viswanathan & Bakker, 2001)

Besides, there is limitation on the achievable steam temperature due to the maximum operating temperature of the material that used (Viswathan *et al.*, 2006). Thus, the material degradation mechanisms and used materials are playing important roles in order to acquire the high efficiency of the power generation. (Calzavara *et al.*, 2005) Ferritic steel T91 is a commonly used material in piping system of boiler tube in power plant (Laverde *et al.*, 2004). In boiler tube of power generation, the outer side of the tube exposed to high temperature and known as dry side, meanwhile the inner side is exposed to high pressure and high temperature steam and knowns as steam side (Nakagawa *et al.*, 2003).

Ferritic/martensitic steel T91, is material currently used as piping system of boiler tube in power plant. (Kurniawan *et al.*, 2016) Hence, the material degradation of the T91 will be taken as consideration for withstand the increasing pressure and temperature of live steam. In real boiler tube of power generation, the outer side of the tube exposed to dry atmosphere, meanwhile the inner side is exposed to high pressure and high temperature steam. These operations at elevated temperature will lead the corrosion rapidly, where the surface layer exposed to aggressive environment. However, the current data is only available for the atmosphere corrosion in dry condition. The high temperature oxidation behavior of ferritic steel for humid condition should be first studied in laboratory level. Data and results from both experiments in dry and humid condition of high temperature will be collected and profiled. (Kurniawan *et al.*, 2016)

In real boiler tube, material must be strong enough. (Nandiyanto *et al.*, 2016) The surface layer on steam-side oxidation must have sufficient chromium content for creating a protective chromium oxide (Cr_2O_3) on the surface. In addition, the material must have high corrosion resistance and mechanical strength in the inner tube surface. (Viswanathan & Bakker, 2001) The exposure atmosphere, which is the steam properties on the inner tube surface might extremely affect the corrosion rate.

However, the existed information on the corrosion properties of the high chromium steels is mainly available for the atmospheric corrosion or dry condition. The high temperature oxidation behaviors of the steel for humid condition are still limited and need further study in laboratory level. Hence, in this work, the oxidation behavior of the T91 is examined in both dry and humid condition.

2. EXPERIMENTAL PROCEDURE

T91 steel sample was cut into flat plate with the dimension of 10 mm x 10 mm x 2

DOI: http://dx.doi.org/10.17509/ijost.v1i2
p- ISSN 2528-1410 e- ISSN 2527-8045

mm. The prepared sample was ground by SiC abrasive paper up to 2000 grits and polished by 3 μm diamond paste. An ultrasonic cleaning is involved for clean all traces of the contamination on the specimen's surface. The cleaning was done in acetone solution for 15 minutes.

Oxidation process was done dry/atmospheric and steam condition, in the apparatus shown in **Figure 1**. Oxidation was conducted at 500-700^{o}C for 12 hours exposing time. Steam oxidation was conducted by flowing Ar-H_2 gas through evaporator and saturator. After oxidation, the weight gain of the oxidized sample was measured and the microstructure was observed by optical microscope and scanning electron microscope (FESEM with EDS).

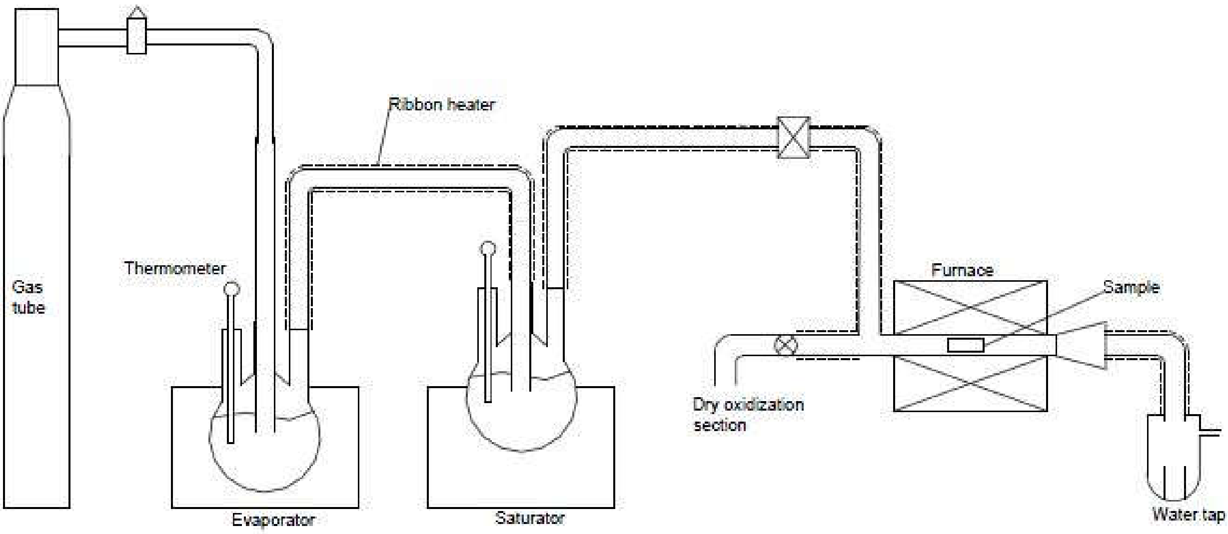

Figure 1. Schematic diagram of high temperature oxidation apparatus.

3. Result and discussion

Figure 2 shows weight gain of the oxidized samples from both dry and humid condition. In dry oxidation there was moderate gain in mass throughtout the experiment. There was no notable mass change from the temperature of 500 to 600°C. However, the mass gain slightly increased to 0.6 mg/cm^2 when the temperature reached to 700°C. While for the humid condition, the mass gain increased gradually over the change of heating temperature. The maximum value of 3.7 mg/cm^2 was observed at 700 °C, which was six times higher than that of the dry condition. Therefore, the increase of temperature in steam environment imparts a significantly increased to oxidation rates at 700°C due to the water vapour content. (Aguero *et al.*, 2013; Lepingle *et al.*,2001) The results demonstrated that the dry condition sample had a better oxidation resistant than the sample that oxidized in steam condition. Therefore, the presence of the water vapour content within the steam environment strongly influenced the oxide scale formation.

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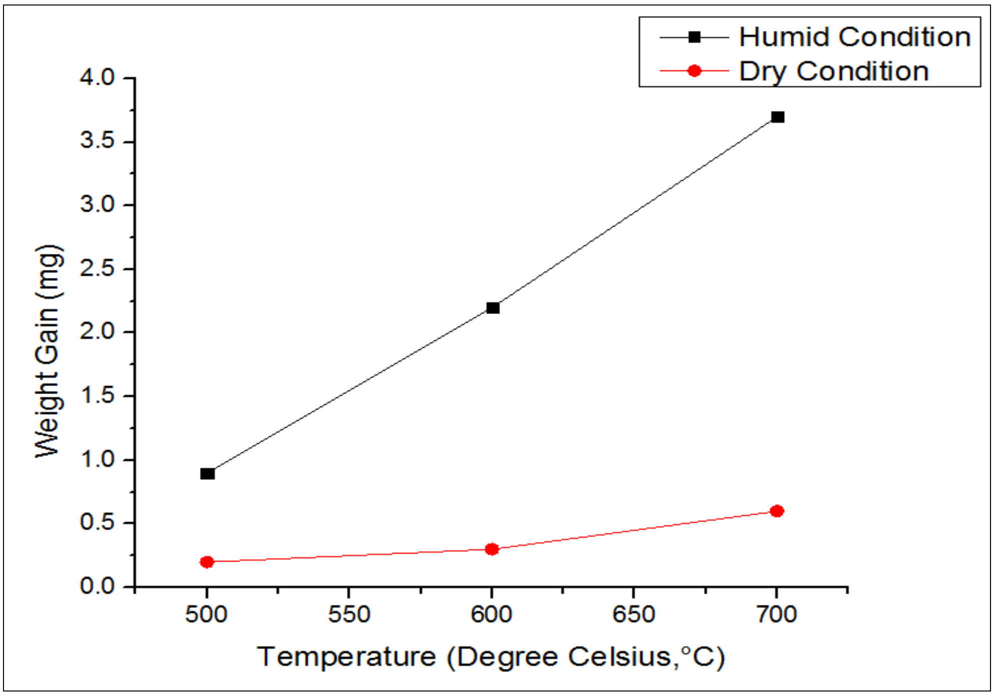
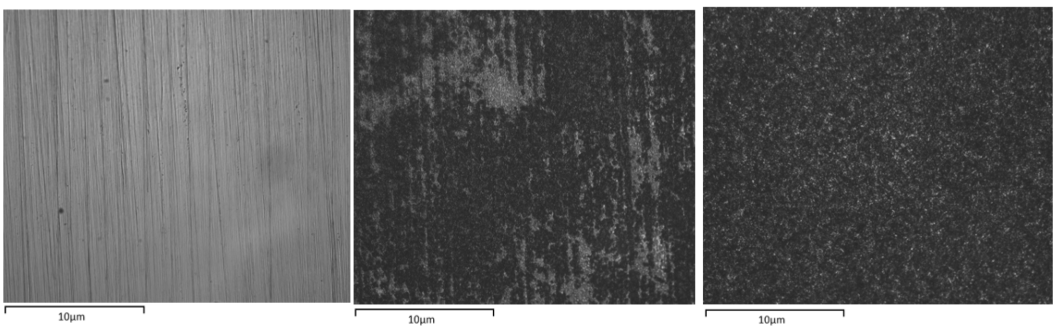


Figure 2. The mass gain throughout the oxidation experiment.

Figure 3 shows optical micrograph images of the specimen exposed to dry and humid conditions. As shown in **Figure 3(b)**, the irregular scale formed on the surface of specimen. The topography of the surface is relatively rough compared to the others. The roughness is caused by the presence of the oxidation products unevenly distributed on the surface. However, there is no crack that been found under the scale. **Figure 3(c)** shows the optical micrograph of the specimen exposed to steam environment. A uniform oxide scale was developed on the surface. It consists of a lot of small size grain and closely packed.



(a) (b) (c)

Figure 3. The surface microstructure of T91 steel at 700°C: (a) Original sample, (b) Dry oxidation, and (c) Steam oxidation

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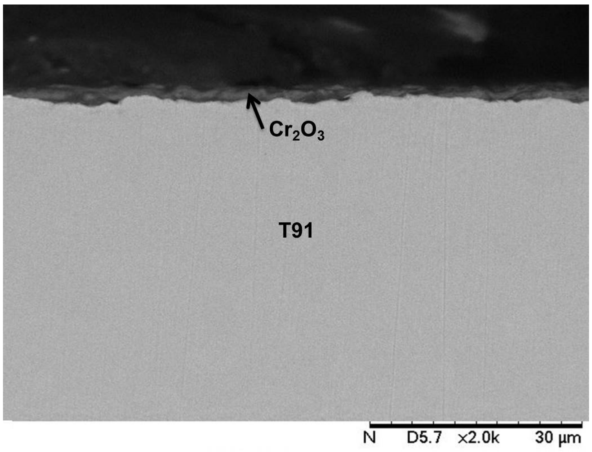
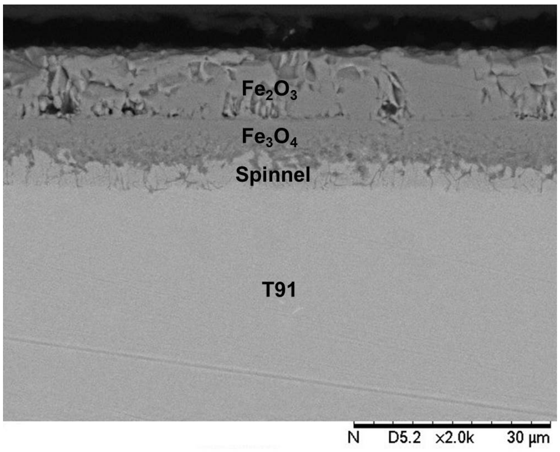
Figures 4 shows the SEM images of oxidized sample in dry and humid conditions. It showed that the oxide scale under the dry oxidation consist of single layer Cr_2O_3 with the thickness of 2.39 ± 0.34 µm. The structure of the oxide scale was dense and free from the pores. Meanwhile, for the oxidized sample in the steam environment, it consists of two oxide layer structures; Iron oxides as the external oxide and spinnel as the internal oxide. The iron oxide itself consist of magnetite as the inner layer, and hematite in the outer layer. The total thickness of the iron oxides is 22.2 ± 1.52 µm. Defect of pores were observed in between hematite and magnetite, which may result in lead to exfoliation of the oxide layer.



(a)



(b)

Figure 4. The SEM cross-sectional image of specimen T91 after oxidation at 700°C for 12 hours in (a) dry condition and (b) humid condition

4. CONCLUSIONS

The oxidation experiments of the ferritic/martensitic steel, T91 within the temperature of 500°C, 600°C and 700°C was conducted in dry and humid condition. It showed that T91 steel still form protective chromia layer on its surface even at 700oC exposure. Meanwhile, the formation of chromia was retarded in humid condition. Non-protective iron oxide layer was formed on the surface of the steel, with the thickness of six times higher than that dry condition. This result proved that water vapor changed the oxidation behavior of T91 steel.

5. ACKNOWLEDGMENTS

This research is fully supported by Fundamental Research Scheme Grant from Ministry of Higher Education Malaysia, under grant No. RDU140110.

6. AUTHOR'S NOTES

The author(s) declare(s) that there is no conflict of interest regarding the publication of this article. Authors confirmed that the data and the paper are free of plagiarism.

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DOI: http://dx.doi.org/10.17509/ijost.v1i2
p- ISSN 2528-1410 e- ISSN 2527-8045

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