Influence of Silicon on Oxidation and Adhesion of Oxide Scale on Hot-Rolled Steel Strips

Thanasak Nilsonthi [1], Seksan Singthanu [2*]

[1]*High Temperature Corrosion Research Centre and Department of Materials and Production Technology Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Thailand*
[2*]*Program in Industrial Management Engineering, Faculty of Industrial Technology, Rajabhat Rajanagarindra University, Thailand: E-Mails:* ssc.sek9@gmail.com

Abstracts: This research focuses on the influence of silicon alloys in hot-rolled steel strips. The steel used in the study was obtained from a hot rolling process with different silicon contents of 0.01, 0.1, 0.2, and 0.3 wt.%. The as-received oxide scale on the hot-rolled steel surface was completely removed by SiC paper and re-oxidized in a horizontal furnace with an atmosphere of 17% H_2O-N_2 at temperatures of 600°C, 650°C, and 700°C for 10 seconds. An investigation of scale adhesion can be done using a tensile testing machine with a CCD camera. The adhesion of the oxide scale to the steel surface was recorded on video. The oxide phase was examined by means of X-ray diffraction (XRD). The microstructure and thickness of the oxide scale were examined by a scanning electron microscope (SEM) with energy-dispersive X-ray spectroscopy (EDS). The results indicated that all steels studied produced oxide scales that consisted of hematite (Fe_2O_3) and magnetite (Fe_3O_4), which contained iron (Fe). The scale thickness tends to increase with increasing temperature, while thickness decreases with increasing Si content in steel. The oxide scale adhesion was indicated by the strain initiating the first spallation during tensile load. The results showed that the strain initiating the first scale spallation tends to decrease with increasing temperature, while scale adhesion increases with increasing Si content in steel. The mechanical adhesion of the oxide scale to the steel substrate was considered in terms of energy. The results indicate that the scale adhesion of steel with 0.3 wt.% Si was higher than that in another sample. It was possible that the presence of an oxide that contains Si at the scale-steel interface, which encourages scale adhesion. The mechanical adhesion energy of the oxide scale was shown in the range of 2-20 J/m^2. The qualitative assessment of scale adhesion in terms of strain initiating the first spallation and mechanical adhesion energy suggested the good adhesion behavior of scale grown in the hot-rolled steel with 0.3 wt.% Si. This result indicates that scale formed on steel with a high silicon content tends to be difficult to remove. There was a need to control the Si content in the hot-rolled steel in a satisfactory way to save energy during the de-scale process.

Keywords: Oxidation, Adhesion, Water Vapor, Hot-Rolled Steel Strips, Silicon Content

1. INTRODUCTION

The surface quality of hot-rolled products is affected by the mechanical adhesion of scale to a steel substrate. The hot rolling process begins by heating a slab in the furnace at a high temperature of approximately 1200-1300°C during 3-4 hours, and then removing any scale with high-pressure water. The slab is placed in a reverse roughing mill and moves forward and backward to reach the desired thickness at high temperatures. The slab is coiled in a coil box and scale removed by hydraulic descaling before it enters the finishing mill. The 7-stand finishing mill is used to reduce the thickness of the slab to the required thickness at temperatures of approximately 820-1000°C. The steel is delivered through a cooling bed to decrease the temperature from 1000°C to approximately 650°C after the finished mill. A down-coiler is used to roll the hot-rolled steel at a temperature range of roughly 500 to 760°C. Hot-rolled steel coil is stored with always oxide scale formed until it is delivered to the customer or for further processing, which may include cold rolling. Therefore, the oxide scale on the surface of hot-rolled steel must be completely removed. This research is interested in studying the formation and adhesion of oxide scale that occur after the coiling temperature of hot rolled steel strips by experimenting with varying the simulated coiling temperature of 600°C, 650°C, and 700°C. This research is also interested in studying the influence of silicon alloys contained in hot-rolled steel strips on the formation and adhesion of oxide scale. This is due to the silicon content added in hot-rolled steel for increasing mechanical and/or electrical properties in blast furnaces (BF) routed or may be attached to it from using scraps as raw materials to produce steel in electric arc furnaces (EAF) routed.

During the hot rolling line, the surface of steel is oxidized, resulting in the formation of iron oxides such as hematite (Fe_2O_3), magnetite (Fe_3O_4), and wustite (FeO) [1-6]. The structure and properties of the oxide scale depend on the alloying elements in the steel [7-11]. No extensive work has studied the effect of silicon on the oxidation and adhesion of the oxide scale formed on hot-rolled steel. It also depends on atmospheric conditions and oxidation temperature, which affect the rate of oxidation [12-16]. As for testing methods for oxide scale adhesion, they are usually tested on stainless steel, such as the indentation test [17], the bending test [18], the inverted-blister test [19], the micro-tensile test is performed in the chamber of a scanning electron microscope [20-22], and our group has developed a macro-tensile test to assess mechanical adhesion. [23-25].

2. MATERIALS AND METHODS

Sahaviriya Steel Industries Public Company Limited (SSI) has supplied the steel in strips with a thickness of 3.2 mm. The Si content in the hot-rolled steel that was received is 0.010, 0.125, 0,188, and 0.292 wt.%, and the other alloying elements generally have similar contents. The process of hot rolling resulted in steel strips with finishing temperatures of 860°C and coiling temperatures ranging from 630 to 650°C. The chemical composition of the steel under study can be found in Table 1.

Table 1. Chemical composition of the studied hot-rolled steel (wt.%).

Hot-rolled steel	C	Si	Cu	Mn	P	S	Fe
0.01	0.170	0.013	0.009	1.047	0.020	0.007	Bal.
0.1	0.135	0.125	0.011	0.900	0.015	0.003	Bal.
0.2	0.120	0.188	0.031	1.395	0.022	0.022	Bal.
0.3	0.164	0.293	0.022	1.163	0.023	0.010	Bal.

A specimen is laser cut from hot-rolled steel strips according to the ASTM E8M standard for setting in a tensile testing machine as shown in Figure 1. The specimen is polished with SiC paper up to 1200 grade for descaling, cleaned under ethyl alcohol with an ultrasonic cleaning machine, dried in air, and rapidly placed in a horizontal furnace. The specimen is oxidized in the furnace with 17% H_2O-N_2 as a simulated hot-rolled steel process atmosphere with a flow rate of 1.2 L/min at 860°C for 10 seconds, and the temperature is reduced by experimental conditions as a simulation of oxidizing at coiling temperatures ranging of 600°C, 650°C, and 700°C for 10 seconds. Nitrogen gas is being used as an inert gas in this study. The experimental method for oxidation runs as shown by the diagram in Figure 2. Before and after oxidizing, the samples are weighed on an electronic microbalance.

The thickness of scales can be estimated using the following equation as pure iron is assumed.

$$Scale\ thickness\ (\mu m) = \frac{\Delta m}{A} \cdot \frac{1}{M_O} \cdot M_{FeO} \cdot \frac{1}{\rho_{FeO}} \cdot 10^4 \quad (1)$$

Here Δm is mass grain change (g), A is area (cm^2), M_O is molecular weight of oxygen (16 g/mol), M_{FeO} is molecular weight of iron oxide (72 g/mol), and ρ_{FeO} is density of iron oxide (5.745 g/cm^3).

The technique for studying crystal structures in steel involves using X-ray diffraction (XRD, D8 advance model). The measurement conditions of XRD such as X-Ray generator of 40 kV, 30 mA, the Cu Kα line (0.15406 nm) with a scan speed of 2.00 º/minute, and step width of 0.02 º. A scanning electron microscope (SEM, Quanta 450) is used to examine the cross-section morphologies of the oxide scale. An electron probe focused on a 1 µm spot is used to perform the energy-dispersive X-ray spectroscopy (EDS) point analyses. The scale adhesion on hot-rolled steel is studied using the CCD camera equipped with a tensile testing machine (Model 5566). A tensile load of 10 kN and a strain rate of 0.04/seconds are used for the tensile loading.

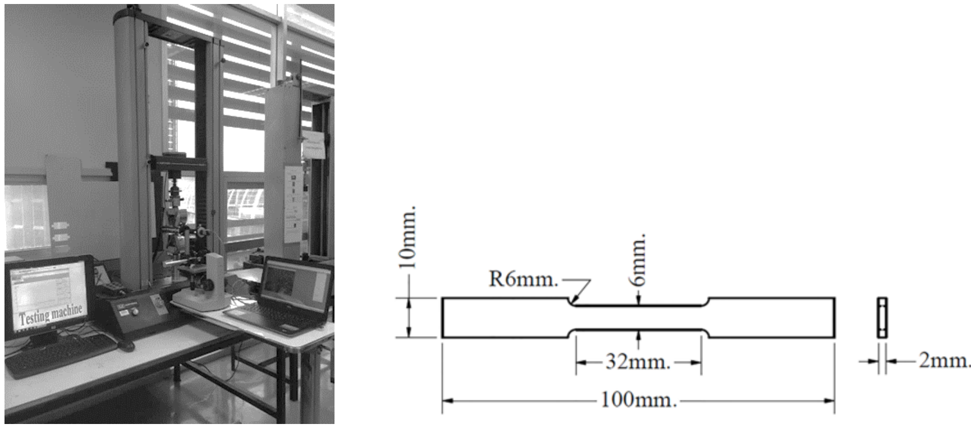


Figure 1. Standard tensile testing machine with an observation setup (left) and a specimen dimension (right).

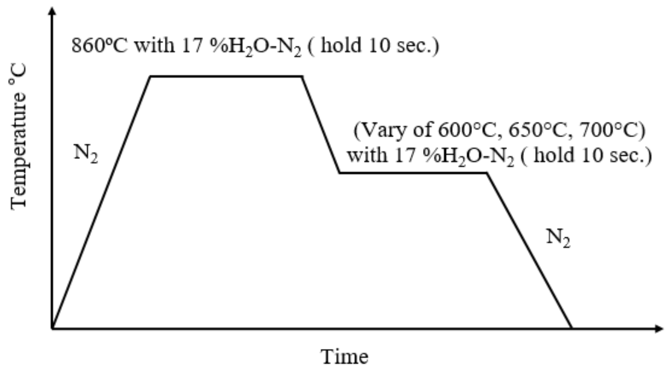


Figure 2. Experimental method for oxidation runs.

The Clausius-Clapeyron equation is used to calculate oxygen in water vapor (17% H_2O) as follows.

$$ln\frac{P}{1\,atm} = \frac{-\Delta H^{l\rightarrow v}}{R}\left(\frac{1}{T} - \frac{1}{373}\right) \quad (2)$$

Here P is the vapor pressure (0.17 atm), ΔH is enthalpy change of reaction (40,893 J/mol), R is the gas constant (8.314 J/mol.K), and T is the temperature (K). The temperature at 17% of the vapor pressure of water can be determined using this equation to be 328.82 K (55.82°C).

3. RESULT AND DISCUSSION

This study examined the differences in silicon content in hot-rolled steel and oxidation during the coiling temperature in relation to the hot-rolling process. The cross-sectional SEM image was used to measure the scale thickness and it was compared with equation (1) as shown in Figure 3. It was seen that the increase in temperature leads to an increase in the thickness of the scale. This was because the molecules have more kinetic energy and move faster due to higher temperatures, resulting in faster diffusion of iron and oxygen. While the thickness decreased with increasing Si content. This was because the silicon-containing oxide acts as a barrier to the diffusion of iron to oxygen. The scale thickness of the 0.01 wt.% Si-containing hot-rolled steel reveals to be significantly higher than that of other Si-containing steel. The test showed that 0.01 wt.% Si steel had a scale thickness in the range of 1.5-2.3 µm under an oxidation temperature of 600-700°C. If compared with 0.3 wt.% Si steel, it can be found that the oxide thickness is in the range of 0.2-0.6 µm.

Figure 4 shows the XRD patterns of the 0.01, 0.1, 0.2, and 0.3 Si-containing hot-rolled steel at temperature of 700°C. The oxide scale was found to consist of hematite (Fe_2O_3) and magnetite (Fe_3O_4) with iron (Fe). It can be observed that on the oxide scale, there were peaks of iron. Considering the phase diagram of iron and oxygen, it was found that at temperatures as low as 570°C, the wustite phase decomposes to magnetite and iron. For this reason, peaks of iron were found on the oxide scale. Related research also found that the hematite layer was the thinnest layer and present at the outermost layer that was exposed to oxygen gas. The magnetite layer was the next layer attached to the steel substrate. Moreover, it was found that the intensity of iron peaks increased for higher Si-containing steel.

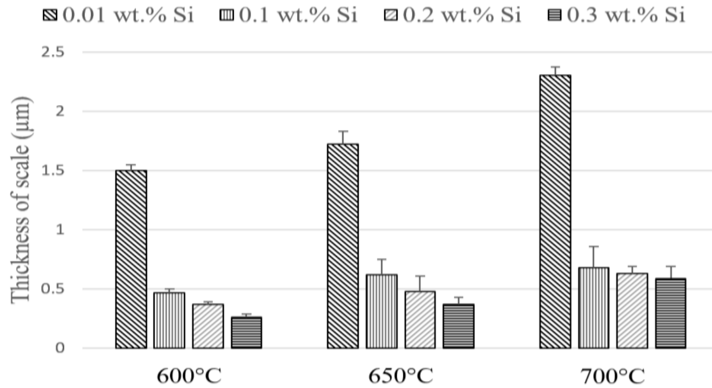


Figure 3. Oxide scale thickness of the Si-containing hot-rolled steel oxidized at 600, 650 and 700°C.

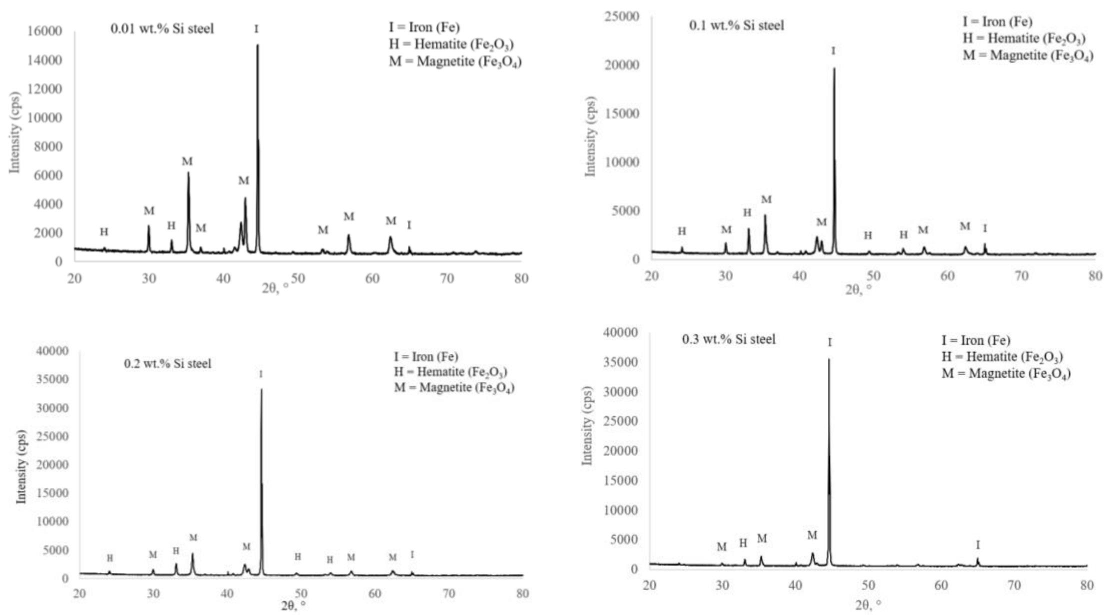
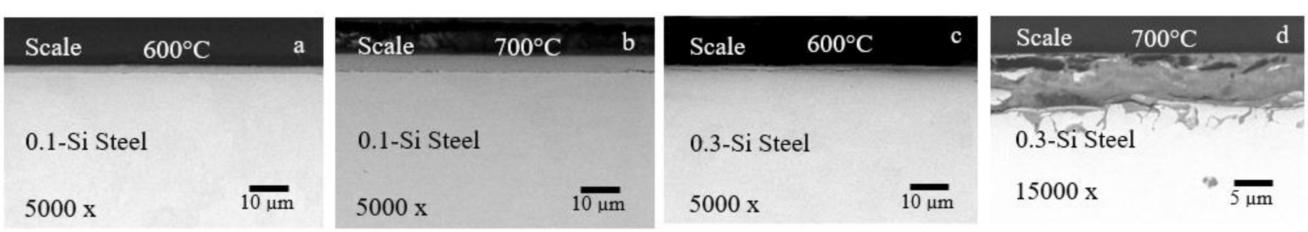


Figure 4. XRD patterns of the 0.01, 0.1, 0.2, and 0.3 Si-containing hot-rolled steel at temperature of 700°C.

The cross-section morphologies of the oxide scale formed on the steel was studied using a scanning electron microscope (SEM) as shown in Figure 5. The scale cross-section morphology of the hot-rolled specimen oxidized in 17% H_2O-N_2 during 10 seconds at 600 and 700°C shows a difference in thickness and morphology of the oxide scale. Internal scale oxidation has caused Fe_2SiO_4 to have a penetration depth observed at the 0.3 wt.% Si/scale interface, as shown by EDS analysis.



e

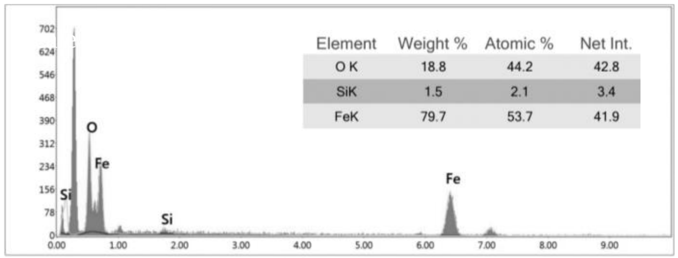


Figure 5. SEM image of a hot-rolled specimen on (a) 0.1 wt.% Si oxidized at 600°C, (b) 0.1 wt.% Si oxidized at 700°C, (c) 0.3 wt.% Si oxidized at 600°C, (d) 0.3 wt.% Si oxidized at 700°C, and (e) EDS pattern at 0.3 wt.% Si/scale interface.

Under tension caused the oxide scale spalls out from the steel substrate. The strain at the first spallation of the scale can be used to describe the adhesion of the scale during tensile loading. This parameter plays a crucial role in comparing the adhesion of hot-rolled steel with different silicon content at different simulated coiling temperatures. The first spallation started rapidly when the adhesion of the scale was lower. The CCD camera focused on the center of the sample during the tensile stress because it was the area with the greatest stress which was 833 N/m^2. The scale on the steel substrate of 0.3 wt.% Si steel was subjected to the imposed strain as shown in Figure 6. The transverse cracks perpendicular to the tensile loading were initially observed, followed by the first scale spallation. It can be seen that the scale spalling increases with the increase in strain. The areas where the oxide has spalled off will turn black in this case.

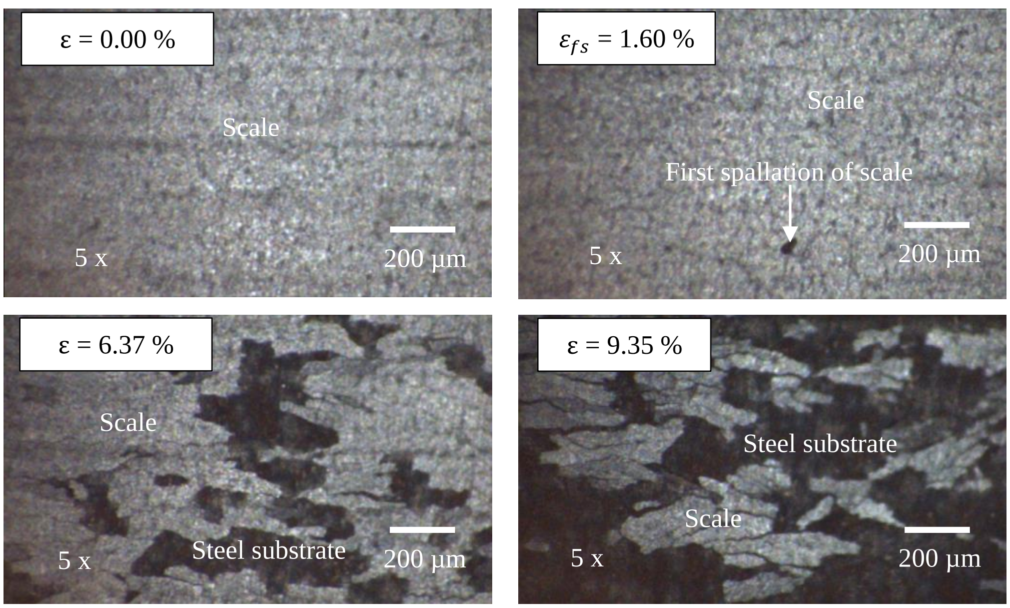


Figure 6. Spallation behavior of the oxide scale under tensile loading on 0.3 wt.% Si steel oxidized at 600°C.

Strain initiating the first spallation of the Si-containing hot-rolled steel at varying temperatures as shown in Figure 7. An increase in temperature has been shown to decrease the strain initiation of the first spallation. The increase in silicon alloying content has been found to increase the strain initiation of the first spallation. The critical strain at the first scale spallation of the steel with 0.3 wt.% Si was higher than that of the lower Si-containing steel. Calculating the mechanical adhesion energy was possible with this parameter and the thickness of the oxide scale. Mechanical adhesion energy represents a forming oxide scale contacted with steel substrate that has an effect on adhesive strength.

The equation provided below was utilized to calculate the mechanical adhesion energy [26]. It was assumed that the oxide scale and the steel substrate had complete adhesion.

$$G_i = W \cdot e \quad (3)$$

Here G_i is mechanical adhesion energy (J/m^2), W is stored energy in the oxide scale until the first spallation (J/m^3), and e is oxide scale thickness (m). The area under the stress-strain curve was used to calculate the stored energy of the oxide scale in the x and y directions, as described in equation $\int \sigma \cdot d\varepsilon$ with Young's modulus of steel and oxide is 210 GPa, Poisson's ratio of steel and oxide is 0.3, compressive residual stress of oxide is -0.2 GPa, and strain at limit of elasticity of oxide is 0.0015. During tensile loading, the steel substrate and oxide scale were in tension. The substrate was deformed plastically, but the scale was still elastic until the first scale spallation took place.

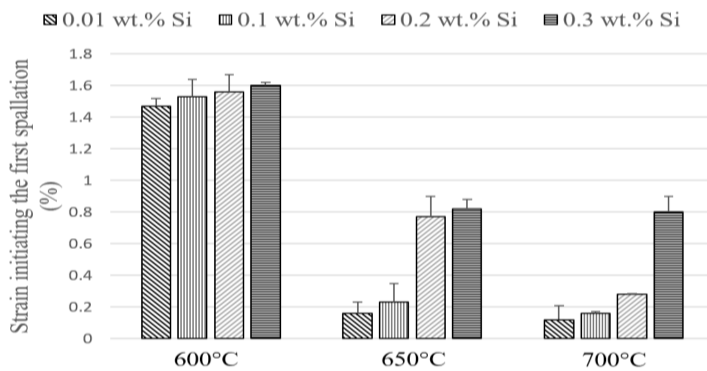


Figure 7. Strain initiating the first spallation of the Si-containing hot-rolled steel oxidized at 600, 650 and 700°C.

Figure 8 depicts the mechanical adhesion energy of hot-rolled steel that contains Si, with information provided in Table 2. The increase in silicon content has been found to increase the mechanical adhesion energy of the scale on steel substrate. Moreover, as the temperature increased, it was found that the adhesion of the scale decreased. It was confirmed that scale adhesion depends on temperature and silicon content. The scale formed at 650 and 700°C show lower adhesion. In this case, steel oxidized at a higher temperature with saturated water vapor had a significant effect. At higher temperatures and relative humidity, the adhesive force between the scale and the steel substrate was lower. This was because the diffusion of interstitial oxygen through the oxide scale has been presented at the scale-steel interface. The scale layer sustained metal oxidation with continuous ion diffusion. The scale layer and the steel substrate were both subjected to stress. The oxide scale can easily be spalled under external forces as a result. However, the formation of the protective oxide layer at the scale-steel interface helps promote scale adhesion of higher Si-containing hot-rolled steel. The compressive stress generated by the growth and cooling of the oxide scale results in the accumulation of residual stress between the innermost layer and the steel substrate, which causes cracking and spalling of the scale during the hot-rolling process.

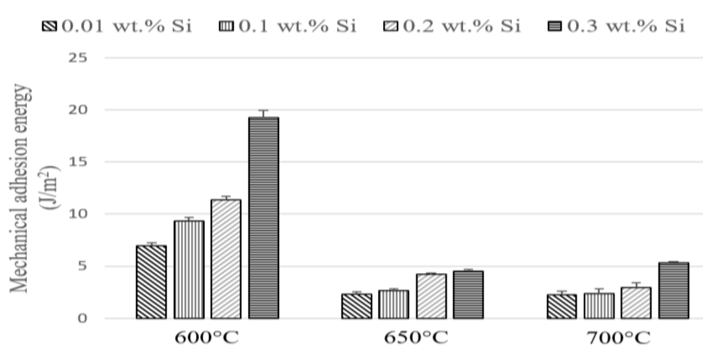


Figure 8. Mechanical adhesion energy of the Si-containing hot-rolled steel oxidized at 600, 650 and 700°C.

Table 2. Experimental results obtained from the study.

Variables	Si content (wt%)			
	0.01	0.1	0.2	0.3

Thickness of scale (μm)	600°C	1.50 ± 0.05	0.47 ± 0.03	0.37 ± 0.02	0.26 ± 0.03
	650°C	1.72 ± 0.11	0.62 ± 0.13	0.48 ± 0.13	0.37 ± 0.06
	700°C	2.30 ± 0.07	0.68 ± 0.18	0.63 ± 0.06	0.59 ± 0.10
Strain initiating the first spallation (%)	600°C	1.47 ± 0.05	1.53 ± 0.11	1.56 ± 0.11	1.60 ± 0.02
	650°C	0.16 ± 0.07	0.23 ± 0.12	0.77 ± 0.13	0.82 ± 0.06
	700°C	0.12 ± 0.09	0.16 ± 0.01	0.28 ± 0.01	0.80 ± 0.10
Mechanical adhesion energy (J/m^2)	600°C	6.93 ± 0.29	9.34 ± 0.32	11.37 ± 0.35	19.26 ± 0.66
	650°C	2.29 ± 0.22	2.67 ± 0.16	4.22 ± 0.11	4.50 ± 0.19
	700°C	2.26 ± 0.36	2.38 ± 0.43	2.93 ± 0.50	5.35 ± 0.10

According to the results, when the silicon content increases in the hot-rolled steel, it tends to increase the scale adhesion. Figure 9 shows that the SEM-EDS revealed the interfacial layer of steel with 0.3 wt.% Si has an oxide containing Si, possibly as SiO_2 or Fe_2SiO_4, because the EDS spectrum includes the peaks of Fe, O, and Si. A Si-enriched oxide present at the steel-scale interface caused an increase in steel passivity and adhesion during the production of the Si-oxide phase. The Si-oxide-formed internal subscale was a barricade to the production of external oxide. Moreover, the Si-oxide layer at the steel-scale interface was also clearly revealed to increase scale adhesion. The results also found that when the silicon content in steel increases, it results in internal oxidation, which was not seen in lower Si-containing steel. This was because a diffusion that was controlled by dissolved oxygen became insufficient during the oxidation of the Si element in the steel. It was unavoidable in the case of Si-containing steel oxidized at high temperatures in a water vapor atmosphere. The oxide containing Si existing at the steel-scale interface promoted mechanical adhesion of scale to the steel substrate, resulting in worsening the picklability of scale during the descaling process in the hot rolling line.

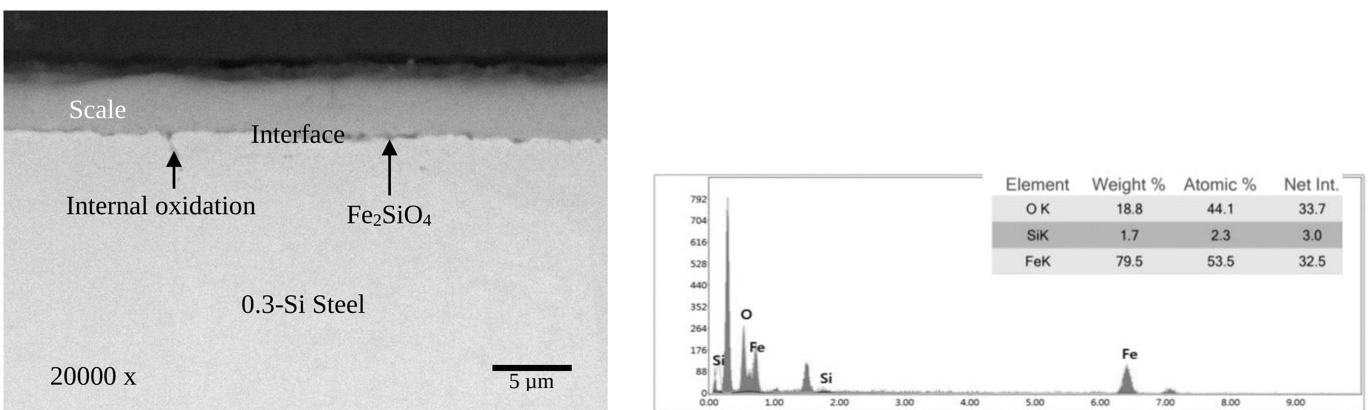


Figure 9. SEM cross sections of 0.3 wt.% Si steel oxidized in 17% H_2O-N_2 during 10 seconds at 650°C (left) and EDS patterns focusing on the scale-steel interface (right).

In this study, the scale formed on Si-containing hot-rolled steel during various coiling temperature oxidations was illustrated in Figure 10. A schematic diagram illustrating the sequence of the formation of contented Si oxide scale in the silicon-containing steels shows a diffusion of oxygen in the steel to form external iron oxide, internal oxidation of silicon incorporating to the formation of Si-contented oxide at the steel-scale interface, oxidation of iron and silicon in the internal oxidation, and silicon-containing oxide formation increasing at the steel-scale interface when silicon in steel increases.

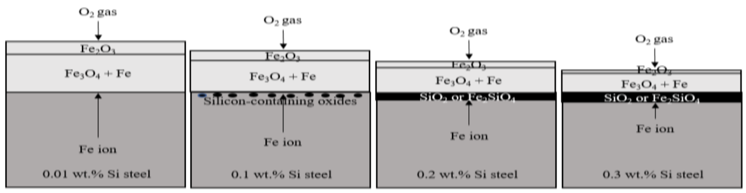


Figure 10. Schematic illustrations of the formation of the oxide scale on the Si-containing hot-rolled steel.

CONCLUSTION

The study focused on hot-rolled steel with different Si contents and studied the effect of simulated coiling temperature on the hot-rolling process. Oxidizing the steel took place in the horizontal furnace with a 17% H_2O-N_2 atmosphere at temperatures of 600, 650, and 700°C for 10 seconds. The thickness of the oxide scale decreases with increasing silicon content, and it was also found that the thickness of the oxide scale increases with increasing temperature. The layers of hematite and magnetite with iron can be formed on the Si-containing steel under the oxidation condition. Internal oxidation appears in steel with a high silicon content when the oxidation temperature increases. The tensile testing machine equipped with a CCD camera was successfully applied to observe oxide scale failure under tensile load. The initial revelation of transverse cracks was followed by scale spallation. Increased strain results in increased scale spallation. The mechanical adhesion energy of scale on Si-containing steel can be calculated to be in the range of 2-20 J/m^2. The results indicate that the mechanical adhesion energy increases with increasing silicon content in hot-rolled steel. The adhesion of the scale was found to decrease significantly when the oxidation temperature increased. At the interface between steel and oxide, it was found that oxide-contented Si was formed, which might be a silicon oxide or fayalite layer, which influenced the rate of oxidation and scale adhesion. Moreover, the thickness of silicon-containing oxide increases with increasing silicon content in the steel. This layer was found to be a barrier for Fe ions to form oxide layers, leading to a lower scale thickness and greater scale adhesion in the steel. Concerning the commercial application, the oxide scale was completely removed if hot-rolled steel was used for cold rolling. The removal of scale was simple in hot-rolled steel with a higher Si content because it has a thinner scale. However, adhesion to a higher scale must be considered. The results obtained herein should control Si content suitably for the easy removal of oxide scale from hot-rolled steel substrate.

ACKNOWLEDGMENT

This research was funded by King Mongkut's University of Technology North Bangkok. Contract no. KMUTNB-64-DRIVE-35. Sahaviriya Steel Industries Public Company Limited was acknowledged for the provision of the hot-rolled steel strips.

REFERENCES

[1] P. Kofstad, *High Temperature Corrosion*, Elsevier Applied Science, London, UK, 1988.
[2] R.Y. Chen and W.Y.D. Yuen, "Oxide-scale structures formed on commercial hot-rolled steel strip and their formation mechanisms," *Oxid. Met.,* vol. 56, pp. 89-118, 2001.
[3] R.Y. Chen and W.Y.D. Yuen, "Oxidation of low-carbon, low-silicon mild steel at 450-900°C under conditions relevant to hot-strip processing," *Oxid. Met.,* vol. 57, pp. 53-79, 2002.
[4] R. Y. Chen and W. Y. D. Yuen, "Review of the high-temperature oxidation of iron and carbon steels in air or oxygen," *Oxid. Met.*, vol. 59, pp. 433-468, 2003.
[5] R. Y. Chen and W. Y. D. Yuen, "Examination of oxide scales of hot rolled steel products," *Iron and Steel Ins. Japan Inter.*, vol. 45, pp. 52-59, 2005.
[6] P. Sarrazin, A. Galerie and J. Fouletier, *Mechanisms of High Temperature Corrosion*, Zurich, Switzerland: Trans Tech Publ, 2008.
[7] S. Chandra-ambhorn, T. Phadungwong and K. Sirivedin, "Effects of carbon and coiling temperature on the adhesion of thermal oxide scales to hot-rolled carbon steels," Corros. Sci., Vol. 115, pp. 30-40, 2017.
[8] S. Chandra-ambhorn, T. Nilsonthi, Y. Wouters and A. Galerie, "Oxidation of simulated recycled steels with 0.23 and 1.03 wt.% Si in Ar-20%H2O at 900°C," Corros. Sci., Vol. 87, pp. 101-110, 2014.
[9] R.Y. Chen and W.Y.D. Yuen, "Isothermal and step isothermal oxidation of copper-containing steels in air at 980-1220°C," *Oxid. Met.,* vol. 63, pp. 145-168, 2005.
[10] S. Chandra-ambhorn, A. Jutilarptavorn and T. Rojhirunsakool, "High temperature oxidation of irons without and with 0.06 wt.% Sn in dry and humidified oxygen," Corros. Sci., Vol. 148, pp. 355-365, 2019.
[11] S. Chandra-ambhorn and K. Ngamkhamand, "High temperature oxidation of micro-alloyed steel and its scale adhesion," *Oxid. Met.*, vol. 88, pp. 291-300, 2017.

[12] A. Atkinson, “Transport processes during the growth of oxide films at elevated temperature,” *Rev. Mod. Phy.*, vol. 57, no. 2, pp. 437-470, 1985.
[13] D. Landolt, *Corrosion et Chimie de Surfaces des Métaux*, PUR Press, France, 1997.
[14] W. Wongpromrat, H. Thaikan, W. Chandra-ambhorn and S. Chandra-ambhorn,“Chromium vaporization from AISI 441 stainless steel oxidized in humidified oxygen,” *Oxid. Met.*, vol. 79, pp. 529-540, 2013.
[15] P. Promdirek, G. Lothongkum, S. Chandra-ambhorn, Y. Wouters and A. Galerie, “Oxidation kinetics of AISI 441 ferritic stainless steel at high temperatures in CO_2 atmosphere,” *Oxid. Met.*, vol. 81, pp. 315-329, 2013.
[16] W. Wongpromrat, V. Parry, F. Charlot, A. Crisci, L. Latu-Romain, W. Chandra-ambhorn, S. Chandra-ambhorn, A. Galerie and Y. Wouters, “Possible connection between nodule development and presence of niobium and/or titanium during short time thermal oxidation of AISI 441 stainless steel in wet atmosphere,” *Mater. High Temp.,* vol. 32, no. 1-2, pp. 22-27, 2015.
[17] X. Sun, W. N. Liu, E. Stephens and M. A. Khaleel,“ Determination of interfacial adhesion strength between oxide scale and substrate for metallic SOFC interconnects,” *J. Power Sources*, vol. 176, pp. 167-174, 2008.
[18] A. Galerie, F. Toscan, E. N’Dah, K. Przybylski, Y. Wouters and M. Dupeux, “Measuring adhesion of Cr_2O_3 and Al_2O_3 scales on Fe-based alloys,” *Mater. Sci. Forum*, vol. 461-464, pp. 631-638, 2004.
[19] J. Mougin, M. Dupeux, L. Antoni and A. Galerie, “Adhesion of thermal oxide scales grown on ferritic stainless steels measured using the inverted blister test,” *Mater. Sci. Eng. A*, vol. 359, pp. 44-51, 2003.
[20] F. Toscan, L. Antoni, Y. Wouters, M. Dupeux and A. Galerie, “Oxidation kinetics and scale spallation of iron-chromium alloys with different titanium contents,” *Mater. Sci. Forum*, vol. 461-464, pp. 705-712, 2004.
[21] G. Bamba, Y. Wouters, A. Galerie, F. Charlot and A. Dellali, “Thermal oxidation kinetics and oxide scale adhesion of Fe–15Cr alloys as a function of their silicon content,” *Acta Mater.*, vol. 54, pp. 3917-3922, 2006.
[22] S. Chandra-ambhorn, F. Roussel-dherbey, F. Toscan, Y. Wouters, A. Galerie and M. Dupeux, “Determination of adhesion energy of thermal oxide scales on AISI 430Ti alloy,” *Mater. Sci. Tech.*, vol. 23, pp. 497-501, 2007.
[23] K. Ngamkham, S. Niltawach and S. Chandra-ambhorn, “Development of tensile test to investigate mechanical adhesion of thermal oxide scales on hot-rolled steel strips produced using different finishing temperatures,” *Key Eng. Mater.*, vol. 462-463, pp. 407-412, 2011.
[24] T. Nilsonthi, S. Chandra-ambhorn, Y. Wouters and A. Galerie, “Adhesion of thermal oxide scales on hot-rolled conventional and recycled steels,” *Oxid. Met.*, vol. 79, pp. 325-335, 2013.
[25] S. Chandra-ambhorn, K. Ngamkham and N. Jiratthanakul, “Effect of process parameters on mechanical adhesion of thermal oxide scale on hot-rolled low carbon steels,” *Oxid. Met.*, vol. 80, pp. 61-72, 2013.
[26] H. E. Evans, “Stress effects in high temperature oxidation of metals,” *Inter. Mater. Rev.*, vol. 40, pp. 1-40, 1995.

DOI: https://doi.org/10.15379/ijmst.v10i2.3338