Environmental Conditions in the Reheating Furnace for High Quality Advanced High Strength Steels for Automobiles

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It is well known that the development of Advanced High Strength Steels (AHSS) is very important for the automotive industry in order to improve fuel efficiency and the reduction of material costs. However, it is particularly difficult to improve the surface quality of AHSS because the high amount of Si, Al, Mn and Ti etc. in AHSS promote selective oxidation, resulting in surface defects. The reheating process in the hot strip mill would cause severe oxidation because it is carried out at elevated temperatures under aggressive environments. In this study a reheating furnace simulator was developed to investigate oxidation phenomena in the reheating process. The environmental gas for the reheating furnace was made by burning coke oven gas with air in the simulator. The air/fuel ratio is precisely controlled by MFC. Ti oxides are easily formed on grain boundaries and Mn and Si oxides are usually formed in inner grains near the steel surface with a small round shape.

Keywords : *oxidation, AHSS, steels, reheating process, coke oven gas.*

1. Introduction

Advanced automotive steels need an excellent combination of high strength and superior surface quality. High temperature oxidation during hot strip rolling is closely related to the surface quality of steels. The hot rolling process consists of several steps: slab reheating, hot rolling and coiling. During the reheating process slabs are exposed under high temperature in a corrosive environment for several hours.

Because of oxidation under these severe conditions, a thick layer of oxide scale forms on the slab surface during the reheating process.[1)-2)] The thickness of this scale is up to several millimeters and consists of thick external oxides and irregular internal oxides. The external oxides are mainly comprised of three layers, namely an outermost thin hematite (Fe_2O_3) layer, an intermediate magnetite (Fe_3O_4) layer, and a thick wüstite (FeO) layer. This scale is usually classified as primary scale and is removed by a hydraulic descaler shortly after the exit from the reheating furnace. The internal oxides are formed by selective oxidation of highly oxidized elements such as Si, Mn, Ti etc. near the metal surface. Usually the internal oxides are composed of composite oxides of Si, Mn and Fe.

It is hard to remove the internal oxides by a hydraulic descaler and it remains on the metal surface during hot rolling, and may cause surface defects on the final steel products. Fig. 1 shows both external and internal oxides on the slab surface during the reheat process in the industrial hot rolling line.

During reheating, steel slabs are heated by radiation from furnace walls and roof and by convective heat transfer by the gas combustion burner. Slabs are charged in the furnace and heated continuously as they are moved along the furnace to a heating temperature of 1150~1300 ℃. The furnace can use fuel oil, natural gas, coke oven gas, blast furnace gas, and some synthetic gas such as a mixture of coke oven gas and blast furnace gas. These fuels are burned with air and the environment in the reheat furnace mainly consists of combination of CO_2, H_2O, N_2, and some excess O_2. Scale growth rate strongly depends on the oxygen concentration in the atmosphere. Initial rates of oxidation depended on oxygen content in the gas mixture and these reaction rates were linear up to oxide thickness of 0.4 to 0.5 mm.[3)] It is reported that H_2O may cause accelerated oxidation of steels at high temperature. H_2O also causes the formation of whisker type Fe oxide on the scale surface.[4)]

The oxidation phenomena in reheat furnace are very complex and it appears that there are a variety of effects,

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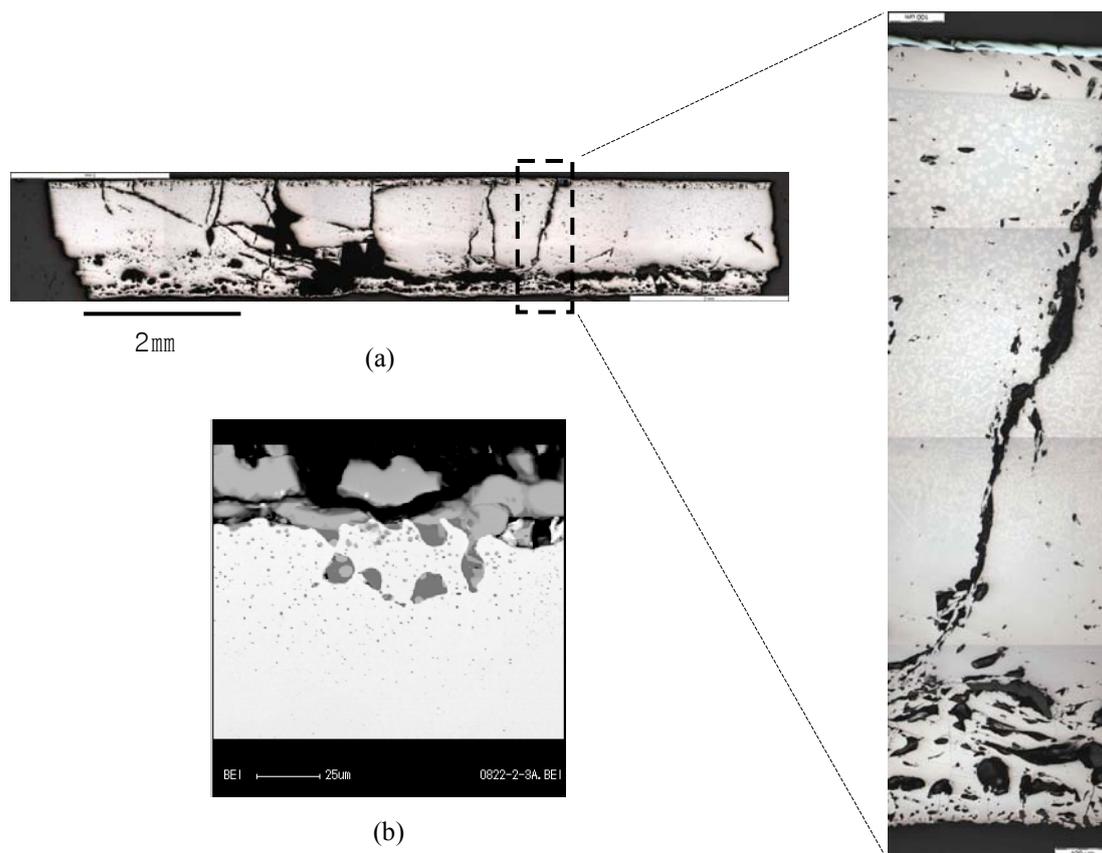[†] Corresponding author: irsohn@posco.com

Fig. 1. Oxides formed on the IF steel slab surface after oxidation in reheat furnace (a) external oxides, (b) internal oxides

depending on heat cycle and gas compositions in the furnace. The variations in the furnace atmospheres are based on the magnitude of the air/fuel ratio. However, limited studies have been carried out on the high temperature oxidation of steels in reheat furnace conditions.[1)-3)] In this study, a reheat furnace simulator was developed to investigate the high temperature oxidation of steels. The temperature and atmosphere are precisely controlled in the simulator. This paper investigates the effect of air/fuel ratio on the high temperature oxidation in reheat furnace for high strength automotive steels. The external oxide morphology and internal oxides were studied under variation of atmospheres.

2. Experimental

The study used commercially available 0.05 Mn-0.05 Ti IF (Interstitial Free) steels and Fe-1.5 Mn-1.0 Si TRIP (Transformation Introduced Plasticity) automotive steels . It was melted in a vacuum furnace and cast into 170x 230x60 t (mm) steel moulds. Specimens were cut from the slab to 15x15x10 t (mm) size. Surfaces of specimens

were finished by fine milling and then ultrasonic cleaned in acetone.

Fig. 2 is a schematic representation of the test apparatus equipped with a gas supply unit, MFC (Mass Flow Controller), a gas combustion unit with an electric furnace and a quartz tube, and a heating unit with an electric furnace and a mulite tube. The gas supply unit comprised high pressure gas containers of fuel gas and air. Gas flow is controlled by an MFC which precisely controlled the gas within 200 ㎖/min..Total inlet gas flow was controlled at about 230 ㎖/min. The test gas moved through fine quartz tubes into the main quartz tube in the combustion furnace. The fuel gas and air reacted in the combustion furnace and the combusted gas moved to the heating furnace. The combusted gas contains a high volume of H_2O. The gas transport line between combustion furnace and heating furnace was heated by heating tape to prevent condensation of H_2O in the line.

The heating furnace heated up to the test temperature and gas supply started 1 hour before the test to ensure that the gas compositions reached equilibrium atmosphere in the test. Table 1 shows the O_2 potentials of the exit
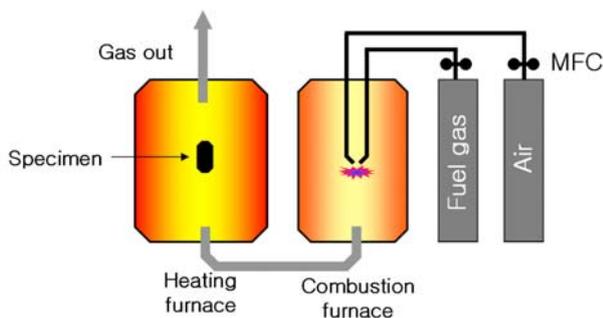
Fig. 2. Schematic diagram for the test apparatus

Table 1. O_2 potentials in exit gas at various air/ fuel ratio at 1473 K (vol%)

Air/fuel ratio	2.8	3.5	4.0	4.5	5.0
Calculated O_2	0.0	3.0	4.7	6.1	7.2
Measured O_2	0.05	3.2	5.2	6.5	7.5

gas of the apparatus with variation of the air/fuel ratio. The calculated values are similar to the measured ones. At the ratio of 2.8, most of O_2 in the air reacted with fuel gas and only limited excess O_2 exists in the atmosphere. O_2 potentials in the atmospheres were increased with the increase of the air/fuel ratio.

The experiments were carried out at 1473 K for 2 hours. The surface morphologies and cross-sections of the specimens tested were usually investigated by scanning-electron microscopy (SEM). The compositions of the scales were measured using Energy-Dispersive X-Ray Spectroscopy (EDS) and an Electron Probe Micro Analyzer (EPMA). X-ray diffraction analysis (XRD, Cu-Ka and Ni-filter) was used to identify the phases of the corrosion products.

3. Results and discussion

Fig. 3 shows oxide surface morphologies of TRIP steel

after oxidation at 1447K for 2 hours under air/fuel ratio from 2.8 to 4.5. Non planar oxides such as a pyramid type formed on the oxide surface at lower O_2 potentials; however, the oxide forms round type and finally planar surface with increase of O_2 in the atmosphere. The growth of non planar oxides such as blades or whiskers is reported on the study of the high temperature oxidation of steels in H_2O containing atmospheres.[4,5] It has been shown that the tiny whisker type oxides comprised of Fe_2O_3 are formed on the scale/gas interface. These whisker type oxides formed with a sub micrometer width and the length is within several micrometers, and it is not formed over 900℃ in humid air.[4] It is suggested that the tiny whiskers grow by surface diffusion of iron cations from the underlying Fe_3O_4 through the tunnels to the whisker tips.[5]

The pyramid type oxides in this study were observed at a size of several hundred micrometers. It is apparent that the pyramid type oxides only grew under low O_2 potentials. Rapp has proposed the growth mechanism of pyramid type oxides.[6] He suggested that short-circuit cation diffusion via scale grain boundaries and dislocations supports oxidation in the intermediate temperature regime, and scale growth at the scale/gas interface takes place at ledges provided by screw dislocations intersecting the surface. These dislocations in the scale are formed by growth stresses or are inherited from the metal.[6] However, the influence of H_2O and O_2 potentials to the formation of pyramid type oxide and the interaction between scale and gas interface is not well understood.

Fig. 4 shows cross sections of the specimens which are shown in Fig. 3. At the air/fuel ratio of 2.8, the pyramids are formed on the surface of the scales. They are not in direct contact with the metal and these oxides are minor parts in comparison to the total growth of oxide scale. Many pores are observed on the upper part of the oxide scales. The upper part of the scale, including pyramids, mainly consist of Fe_3O_4, and a relatively thick FeO oxide

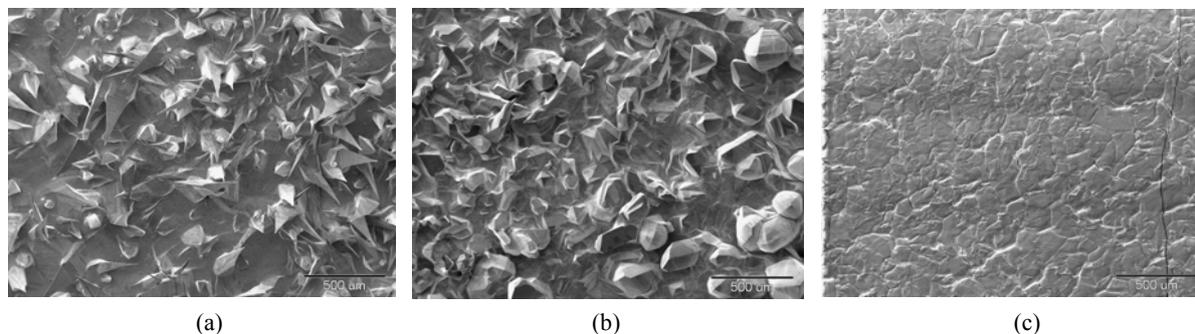
(a)   (b)   (c)

Fig. 3. Surface morphologies of TRIP steels oxidized in reheat furnace simulator in 1447K for 2 hours under various air/fuel ratio; air/fuel ratio is (a) 2.8, (b) 3.5, (c) 4.5

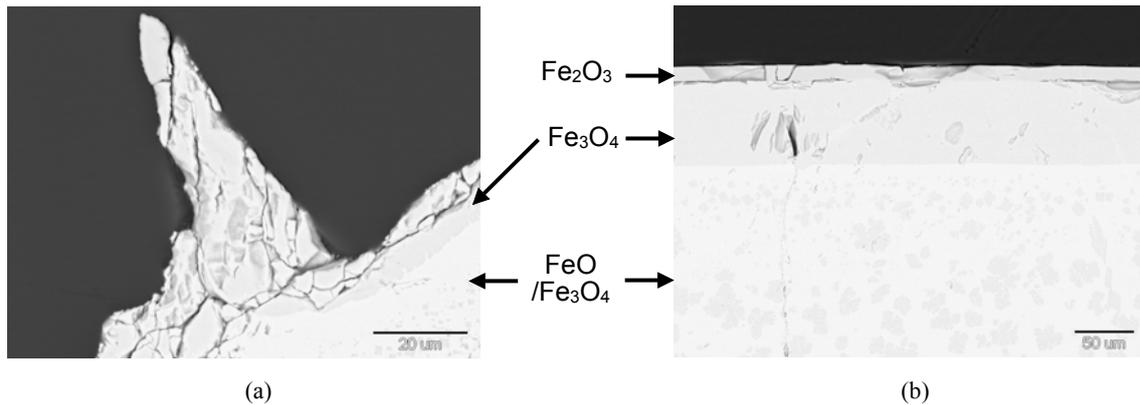(a)   (b)

Fig. 4. Cross sections of TRIP steels oxidized in reheat furnace simulator in 1447K for 2 hours under various air/fuel ratio; air/fuel ratio is (a) 2.8, (b) 4.5

formed in the lower part of the scale. Only thin and isolated formations of Fe_2O_3 are observed on the scale surface. It is considered that there is not enough O_2 for the formation of Fe_2O_3 on the surface of oxide scales at the low air/fuel ratio. It seems that the pyramid type of oxides are formed in low O_2 and H_2O containing atmosphere at elevated temperature. Former study showed that only planar oxides are formed over 900℃ with enough O_2 potential. It is considered that the initial formation of continuous Fe_2O_3 layer is very important for the formation of the planar oxide growth. At the air/fuel ratio of 4.5, however, the scales formed layer by layer as shown in Fig. 4 (b). A stable Fe_2O_3 layer formed continuously as the outmost oxide layer. In this investigation, the planar oxide as shown in Fig. 3(a) and Fig. 4(b) was observed when the air/fuel ratio is over 4.0.

Fig. 5 shows the morphologies of scale/metal interface and internal oxidation of IF and TRIP steels after oxidation at 1447K for 2 hours under air/fuel ratio of 4.0~4.8. Internal oxides formed as irregular shapes in IF steel. On the contrary, Fayalite (Fe_2SiO_4) formed between the external Fe oxides and the metal surface in the TRIP steel. Small circular type internal oxides are formed beneath the metal surface. In thermodynamic calculation, it is considered that the circular internal oxides are composed of composite oxides of SiO_2, $MnSiO_3$ and Fe_2SiO_4. The internal oxides also contain small amounts of P, and the P concentration increases with the increase in the size of internal oxides.

Fig. 6 shows scale growth with variation of the air/fuel ratio. The growth of external oxide indicates the width of the external oxide scales. The internal oxides indicated in the graph are the depth of internal oxide from the metal surface. The formation of internal oxides in IF steel is irregular and the depth of internal oxide in Fig. 6 (a) in-
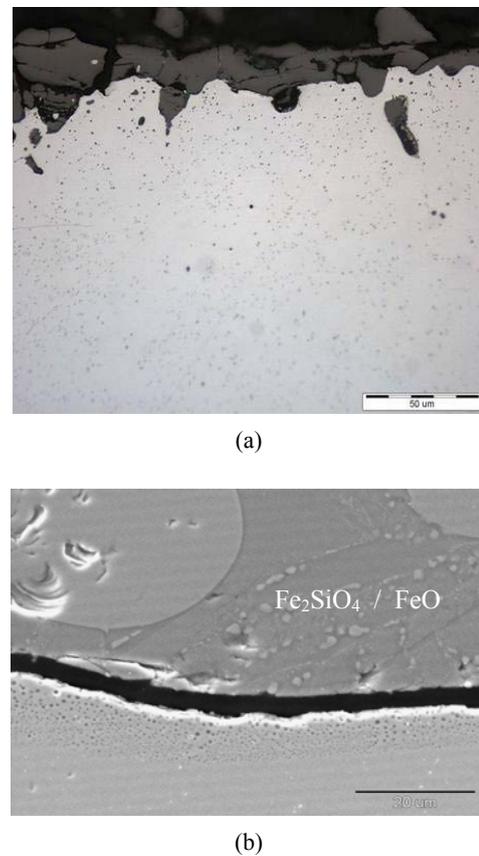

(a)

(b)

Fig. 5. Sub scales formed on the steel surface in reheat furnace simulator in 1447K for 2 hours (a) IF steel at fuel/air ratio as 4.8 (b) TRIP steel at fuel/air ratio as 4.0

dicates the maximum depth of internal oxide in the tested specimen.

Both the external and internal oxides in IF steels grew linearly with the increasing of the air/fuel ratio. The external oxide growth in TRIP steels shows similar to that
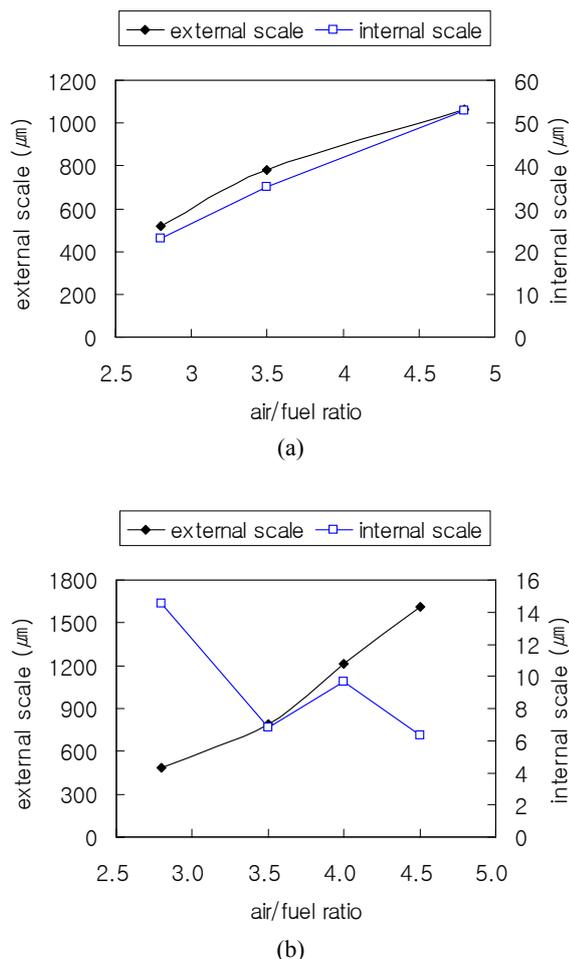
(a)

(b)

Fig. 6. The external and internal scale growth of the IF and TRIP steels at 1447K for 2hours with variation of air/fuel ratio (a) IF steels, (b) TRIP steels

of IF steels, however, the depth of internal oxides does not depend on the growth of external oxides or air/fuel ratio. The different internal oxidation behavior of the two steels is manly due to the Si enriched oxides between Fe oxides and the metal surface as shown in Fig. 5 (b). This

layer mainly consists of Fe_2SiO_4 and it prevents O_2 diffusion from outside to the metal surface. The other reason to consider is the pore density in the external oxide scale. The external oxides formed on TRIP steels contain some pores and it was observed that these pores decrease with the increase of the air/fuel ratio.

4. Conclusions

The high temperature oxidation behaviors of an IF steel and a high strength TRIP steel were investigated in a simulated reheat furnace conditions at 1473K with various air/fuel ratio. The results obtained may be summarized as follows:

(1) The growth of the external oxide scales on the tested steels increased with the increase of the air/fuel ratio in the range of 2.8~4.5. The non-planar oxides such as pyramid type oxides grow at a lower air/fuel ratio. The non-planar oxides gradually change to planar oxides with the increase of the air/fuel ratio.

(2) The total growth of oxide scales on the tested steels increased in a virtually linear rate with the increase of air/fuel ratio.

(3) The maximum depth of internal oxides in IF steels grew linearly with the increasing of the air/fuel ratio, however, in TRIP steels the growth of internal oxides does not depend on the air/fuel ratio. This is because the formation of an Fe_2SiO_4 layer formed between external Fe oxide and the metal surface as a diffusion barrier.

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