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JOURNAL OF IRON AND STEEL RESEARCH, INTERNATIONAL. 2016, 23(8): 739-744

Effect of Scale Formation on Copper Enrichment Behavior in Continuously Cast Slab

Nan WANG[1], Jin XU[1], Shan YU[1], Guang-zong ZHANG[1], Guang-hao CHEN[2], Min CHEN[1]

(1. School of Metallurgy, Northeastern University, Shenyang 110819, Liaoning, China; 2. School of Computer Science and Engineering, Northeastern University, Shenyang 110819, Liaoning, China)

Abstract: Copper enrichment behavior in continuously cast slab induced by scale formation during continuous cooling was experimentally investigated, and the effects of initial slab surface temperature and oxygen potential in atmosphere were discussed. The results showed that a loose scale adhered to the substrate was formed in H_2O-N_2 atmosphere at higher slab surface temperature compared to a gap formed between the scale and the steel substrate after continuous cooling in H_2O-O_2-N_2 atmosphere. Under the condition of continuous cooling in H_2O-N_2 atmosphere, the copper enrichment occurred both within the loose scale and at the scale/steel interface with simultaneous Ni enrichment near the interface at higher slab surface temperature. The combined effects of the loose scale and nickel enrichment were thought to promote the back-migration of Cu-rich phase from the interface and occlusion within the scale layer. While in H_2O-O_2-N_2 atmosphere, the Cu enrichment was found on the steel side and the formed gap prevented the migration of Cu to the scale.

Key words: copper enrichment behavior; slab surface temperature; oxygen potential; atmosphere; scale; nickel enrichment

The use of scrap in steelmaking, especially in electric arc steelmaking, induces inevitable residual elements problem. The residual elements such as copper, tin and arsenic which have oxidation potential less than iron, are retained in the steel because they are difficult to be removed in steelmaking process[1]. During subsequent processing operations such as continuous casting and hot rolling, residual elements tend to concentrate on the steel/scale interface as the surface of steel is oxidized and further penetrate along the grain boundary. This promotes cracking known as surface hot shortness caused by the penetration of the Cu-rich phases into the grain boundaries[2-4]. In the past, enrichment of residual elements during hot rolling and its influence on the surface quality of hot rolled plate have been extensively studied[5-8].

On the other hand, significant residual build-up has also been detected at the scale/steel interface in continuously cast products during continuous casting. The extent of residual build-up may depend on these factors such as the rate of scale formation, the occlusion extent of the residual elements into the scale and the diffusion rates of the elements from the surface to the steel matrix[9]. Additionally, different from the situation of the steel stock reheating, this residual element enrichment during continuous casting process has been related to the rapid oxidation of the slab surface with heat release in the secondary cooling zone. Thus, history of scale formation would have an effect on the copper enrichment behaviour[10-12].

In the present work, a laboratory experiment was conducted involving the heated specimens of the commercial continuously cast slab which were continuously cooled in H_2O-O_2-N_2 and H_2O-N_2 atmosphere respectively to investigate the copper enrichment behavior induced by the scale formation, mainly the effects of initial slab surface temperature and oxygen potential in atmosphere during continu-

Foundation Item: Item Sponsored by National Natural Science Foundation of China (51174052, 51374062, 51574065, 51574066)

Biography: Nan WANG, Doctor, Professor; **E-mail**: wangnan@mail.neu.edu.cn; **Received Date**: November 24, 2015

ous cooling process.

1 Experimental

A type of Cu-bearing continuously cast slab with the chemical composition listed in Table 1 was used. The contents of copper and nickel in the slab were 0.52 and 0.422 mass%, respectively. Sample preparation of continuously cast slab was similar to that in the previous work[13]. To ensure that the oxidizing surface of slab sample was the chilled layer composed of fine equiaxed grain, the upper layer of commercial continuously cast slab was firstly taken down and cut into rectangular samples with dimensions of 10 mm×10 mm×5 mm. Then, the original scale and mold flux adhered to the top surface of slab sample were removed by SiC abrasion paper and cleaned ultrasonically in ethanol.

In the laboratory experiment, the prepared slab samples were firstly heated to the desired temperature (1150 ℃ or 1250 ℃) in a horizontal tube furnace and held at the temperature for 5 min in nitrogen gas flow. After the sample surface temperatures reaching the desired ones, the slab samples were then rapidly taken out of the heating furnace and put into another horizontal atmosphere-controlled furnace, allowing continuous cooling to 800 ℃ in 63 vol.% H_2O-N_2 or 63 vol.% H_2O-8 vol.% O_2-N_2 oxidizing atmosphere, respectively. Of the two continuous cooling cases from 1150 ℃/1250 ℃ to 800 ℃, the duration time was about 18−22 min. Finally, the sample was removed from the atmosphere-controlled furnace to cool consecutively to room temperature in air. The whole experimental process was designed to investigate the scale formation as well as the induced copper enrichment behaviour during the simulated continuous cooling process in the secondary and air cooling zones. The experimental conditions are shown in Table 2.

After oxidation experiment, the cross-section of the scale layer was observed to investigate the microstructure by scanning electron microscopy (SEM), and element distributions inside the scale layer and the steel substrate were respectively analyzed by energy dispersive X-ray spectrametry (EDS).

Table 1 Chemical composition of Cu-bearing continuously cast slab mass%

C	Si	Mn	P	S	Ni	Cr	Al	Cu
0.080	0.277	0.89	0.094	0.002	0.422	0.425	0.0635	0.52

Table 2 Experimental condition of scale formation and Cu enrichment behaviour

Initial slab surface temperature	Continuous cooling condition
1150 ℃, 1250 ℃	1150 ℃ or 1250 ℃→800 ℃ in 63 vol.% H_2O-N_2 or 63 vol.% H_2O-8 vol.% O_2-N_2→ Room temperature in air

2 Results and Discussion

2.1 Microstructure and adhesion status

Figs. 1(a) and 1(b) show the scale microstructures and adhesion status to the steel substrate after continuous cooling from the different initial slab surface temperatures (1150 ℃ and 1250 ℃) to 800 ℃ in 63 vol.% H_2O-N_2 atmosphere, and then consecutively cooling to room temperature in air. It can be noted that the scales formed under the continuous cooling condition in 63 vol.% H_2O-N_2 atmosphere show a relatively tight adhesion to the substrate irrespective of the different initial slab surface temperatures, while a loose microstructure with some microcracks inside the scale layer is observed at the higher slab surface temperature of 1250 ℃. In contrast, for the case of continuous cooling in 63 vol.% H_2O-8 vol.% O_2-N_2 atmosphere, the adhesion between the scale and substrate is poor for both the specimens with the different initial slab surface temperatures of 1150 ℃ and 1250 ℃ respectively, and a distinct gap is formed at the scale/steel interface, as shown in Figs. 2(a) and 2(b). This poor adhesion between steel matrix and scale can be explained as that for the continuous cooling case in 63 vol.% H_2O-8 vol.% O_2-N_2 atmosphere, the oxidation rate of the slab surface is higher than that in 63 vol.% H_2O-N_2 atmosphere and the movement of iron ions from the steel matrix to the reaction site can cause loss of the scale adhesion and thus induce a gap at the interface, especially for the more rapid oxidation case in H_2O-O_2-N_2 atmosphere[14]. Additionally, the loose scale microstructure with some microcracks is thought to be caused by the volume expansion stress due to the phase transformation from wustite (face-centered cubic lattice crystalline with crystal axis of