論文 / 著書情報
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Title(English)	Thermal Conductivity/Diffusivity Determination and Prediction for Iron Oxide Scale System
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論 文 要 旨

THESIS SUMMARY

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要旨（英文800語程度）
Thesis Summary（approx.800 English Words ）

In the steel making process, strict control over the water spray cooling process is essential to obtain high-quality steels. However, iron is easily oxidized at high temperatures, and possesses an iron oxide scale on the surface of iron, which affects the cooling rate and bring distortion and cracking in the final steel products. Thus, the thermal conductivity and thermal diffusivity of the iron oxide scale are essential. However, because of the complex structure of iron oxide scale, there have been few reports on the thermal conductivity/diffusivity of iron oxide scales. Consequently, the present work aims to obtain the thermal diffusivity/ conductivity of FeO, Fe_3O_4 and multi-layered iron oxide scale consists of FeO, Fe_3O_4 and Fe_2O_3, and to propose the prediction equation of thermal conductivity for actual iron oxide scale.

Iron plates (99.99% purity) were selected as substrates, on which FeO, Fe_3O_4 or multi-layered scale were produced on both surfaces. For FeO samples, the iron substrates were oxidized at 973 K in air for 1.5- 5.5 h to obtain an iron oxide scale consists of FeO, Fe_3O_4 and Fe_2O_3, and then the latter two were reduced by heating in a nitrogen atmosphere at 1273 K for 1.5-3 h; For Fe_3O_4 samples, the iron substrates were oxidized at 823 K for 172.8- 604.8 ks in the Ar- 0.84%H_2- 15.6%H_2O gas mixture; Whereas, for multi-layered scale samples, the iron substrates were oxidized at 1173 K in air for 40- 620 s. The thicknesses of scale were adjusted by controlling the heating time and the successive polishing, and were measured by the cross-sectional scanning electron microscopy (SEM) images.

The thermal diffusivity/ conductivity values were measured with the laser flash method from room temperature to 1173 K. The front surface of the sample was heated by a laser pulse and the temperature change at the back surface was measured by a radiation thermometer. The thermal diffusivity and conductivity of scale were calculated from the apparent heat diffusion time (the time when the resulting temperature rises to the maximum value) with the analysis technique for multi-layered samples.

The measured thermal diffusivity/ conductivity values increase with the increasing of the scale thickness, which suggests that there is an interfacial heat resistance between scale and iron substrate. Consider the measured heat resistance of the scale consists of the heat resistance of the scale itself and the interfacial heat resistance ($R_{\mathrm{scale/iron}}$), finally, the interfacial heat resistance can be obtained with the following equation:

$$x_{\mathrm{scale}}/k_{\mathrm{scale-meas}} = x_{\mathrm{scale}}/k_{\mathrm{scale}} + R_{\mathrm{scale/iron}}$$

Where d_{scale} is the scale thickness, $k_{\mathrm{scale-meas}}$ is the measured thermal conductivity and k_{scale} is the thermal conductivity of scale itself. Plots the value of $x_{\mathrm{scale}}/k_{\mathrm{scale-meas}}$ with x_{scale} of the samples with different scale thicknesses, where the intercept represents the interfacial heat resistance. The interfacial heat resistance between FeO/Fe and between multi-layered scale/Fe were derived as 7.3×10^{-7} m^2KW^{-1} and 6.4×10^{-7} m^2KW^{-1}, respectively, at room temperature. The obtained interfacial heat resistance was used to correct the measured thermal conductivity/ diffusivity of scale.

In addition, depending on the Fe-O phase diagram, the FeO decomposition occurs below 843 K, and Fe_3O_4 and α-Fe generate because of the decomposition. It suggests that the scale phase transformation affects the thermal conductivity/ diffusivity of the scale. Thus, in order to clarify the real thermal conductivity/ diffusivity value of the scale layer, the phase transformation behavior during the laser flash measurement were observed by a scanning electron microscope with energy-dispersive X-ray spectroscopy (SEM-EDS) with the cross-sections of scales at each temperature. The results show that, for example, in the case of single FeO scale sample, granular Fe_3O_4 precipitates and eutectoid structures of Fe_3O_4 and Fe generated at 676 K; and granular Fe_3O_4 and Fe precipitates exist at 859 K to 1164 K. The volume fractions of each substance

were measured with GIMP software, and were used to correct the thermal conductivity/ diffusivity of scale. The values were corrected with the effective thermal conductivity equation of a system with a matrix and dispersed phases. The corrected thermal conductivity/ diffusivity values for FeO and Fe_3O_4 scale largely decrease with the increasing temperature, which are dominated by the phonon mean free path.

Finally, the thermal conductivity prediction equation for the actual iron oxide scale system (k_{scale}) was proposed with the consideration of the multi-layered structure, the thermal conductivity of each substance and the phase transformation, as shown following:

$$\frac{x_{\mathrm{scale}}}{k_{\mathrm{scale}}}=\frac{x_{\mathrm{FeO}}}{\frac{3k_{\mathrm{pore}}+2(1-f_{\mathrm{pore}})(2k_{\mathrm{FeO}}-k_{\mathrm{pore}})}{3k_{\mathrm{FeO}}-2(1-f_{\mathrm{pore}})(2k_{\mathrm{FeO}}-k_{\mathrm{pore}})}k_{\mathrm{FeO}}}+\frac{x_{\mathrm{Fe3O4}}}{k_{\mathrm{Fe3O4}}}+\frac{x_{\mathrm{Fe2O3}}}{k_{\mathrm{Fe2O3}}}$$

Where x_{scale}, x_{FeO}, $x_{\mathrm{Fe_3O_4}}$ and $x_{\mathrm{Fe_2O_3}}$ is the thickness of the whole scale, FeO layer, Fe_3O_4 layer and Fe_2O_3 layer, respectively; k_{FeO}, k_{pore}, $k_{\mathrm{Fe_3O_4}}$ and $k_{\mathrm{Fe_2O_3}}$ is the thermal conductivity of FeO, air, Fe_3O_4 and Fe_2O_3, respectively. The thermal conductivity of the actual iron oxide scale (21.8 μm), which is obtained in the hot-rolling process, was calculated with above prediction equation; where the temperatures at the iron oxide scale surface and at the interface between iron oxide scale and iron substrate is assumed to be about 373 K and 1173 K, respectively. The predicted thermal conductivity value was derived as 2.0 $Wm^{-1}K^{-1}$, which is about 1/24 of the thermal conductivity of iron substrate.