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NEW RADIATION PYROMETER USING REFLECTED INFORMATION

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Abstract : It is very difficult to measure accurately the temperature of steel sheet using a radiation pyrometer when surface emissivity changes drastically . In order to solve this problem we propose a new radiation pyrometer using the information of reflectance.

Keywords : Radiation Pyrometer , Emissivity Compensation , Reflectance

1 INTRODUCTION

We have monitored the behavior of spectral emissivity of some metal sheets during the oxidation process to evaluate temperature measurement accuracy. Measured emissivity values range from about 0.3 to about almost 1. So we concluded that we must measure the temperature by using in-situ emissivity values. In order to solve this problem, we developed a new type of radiation pyrometer using the information of reflectance. On-line emissivity is estimated from measured reflectance at two angles. In this paper, we describe the principle of this pyrometer and the results of on-line measurement accuracy of the proposed pyrometer.

2 BEHAVIOR OF SPECTRAL EMISSIVITY OF STEEL SHEET IN OXIDATION PROCESS

We measured the spectral emissivity of some metal sheets in a controlled atmosphere. A schematic diagram of the furnace is shown in Fig.1.The temperature of a sample sheet was measured by a fine K-type thermocouple. Thermal radiation from the sample was spectro-scoped by using four interference filters. Spectral emissivity was calculated from the measured temperature by a thermocouple and spectral radiation intensity. Central wavelengths of these interference filters were 0.93μm, 1.11μm, 1.38μm and 1.65μm.

Figure 2 shows an example of emissivity measurement results of a cold rolled steel. Emissivity of all the samples increased steadily in the early stage of oxidation. Emissivity at shorter wavelengths increased earlier than at longer wavelengths. Emissivity of most samples oscillated as oxidation progressed. Afterwards the oscillation amplitude of emissivity value gradually decreased, and it approached to the fixed value which was well known for emissivity of oxidized steel.

With these experiments, it was clear

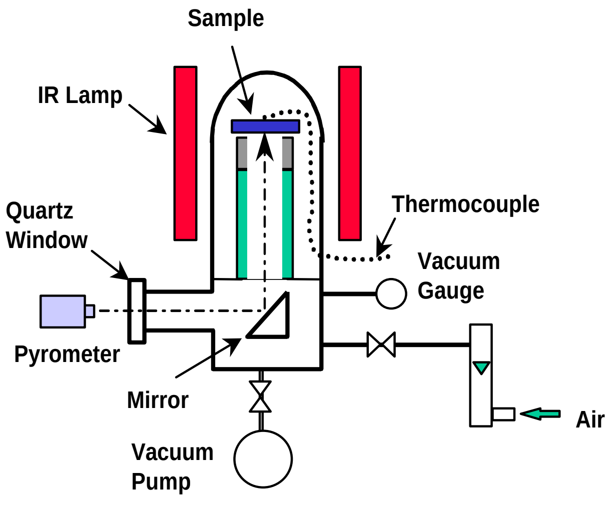

Fig.1 Schematic diagram of IR vacuum furnace

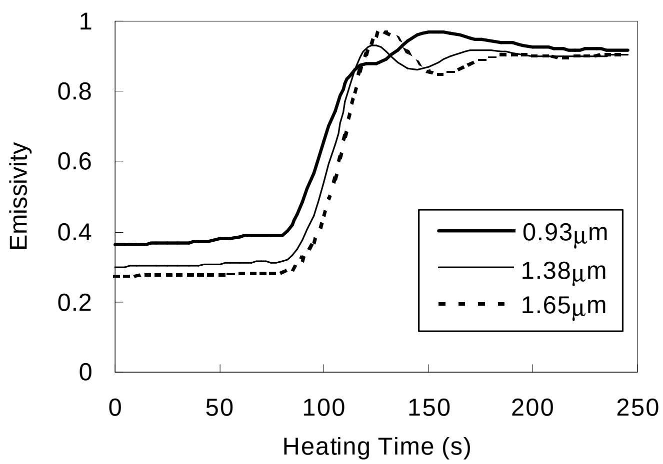

Fig.2 Emissivity Change of cold rolled steel in oxidation

that emissivity was drastically changed and its behavior was very complex during the oxidation process. Therefore real-time emissivity compensation methods are necessary in order to measure temperature accurately using a radiation pyrometer in the oxidation processes.

3 PRINCIPLE OF THE NEW PYROMETER

3.1 Characteristics of reflected light from cold rolled steel sheet

Emissivity of an opaque material is calculated from a hemispherical reflectance by Kirchhoff's law.

$$\varepsilon = 1 - R \quad (1)$$

where ε is emissivity and R is a hemispherical reflectance.

In order to evaluate the hemispherical reflectance, we measured the angular distribution of reflected light of cold rolled steel sheet. The surface roughness of the samples was 0.48,0.68 and 1.33μm. These are typical values for steel sheet which is annealed on a continuous annealing line. The experimental results are shown in Fig.3. The light source was a Light Emitting Diode (LED) whose central wavelength was 880nm.

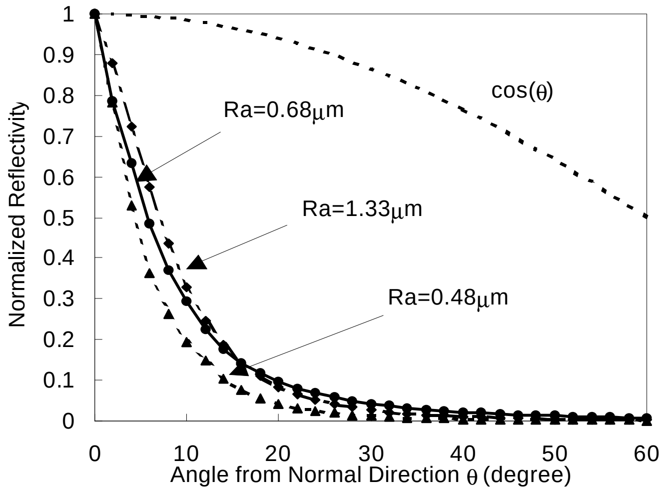

Fig.3 Angular distribution of reflection for cold rolled steel

Hemispherical reflectivity is defined by equation (2) .

$$R = \int R(\theta)\cos\theta d\omega = \iint R(\theta)\cos\theta \sin\theta d\phi d\theta = \pi \int R(\theta)\sin 2\theta d\theta \quad (2)$$

where $R(\theta)$ is the reflectivity at θ angle, θ is the angle from the normal direction, zenith angle , ω is a solid angle and φ is an azimuthal angle. As cold rolled steel sheet has uniform and random surface conditions, it is assumed that reflectivity is only a function of θ direction and does not depend on φ direction.

From the angular distribution of reflected light, we calculated the light intensity from normal to zenith angle(θ) and calculated the total reflectance normalized by hemispherical reflectance. If we integrate the reflected light from normal to 35 degrees, normalized reflectance is from 0.85 to 0.93. If we correct the measured light intensity from normal to 35 degrees by using an average of the above values, we can obtain the hemispherical reflectance within 4.5% error.

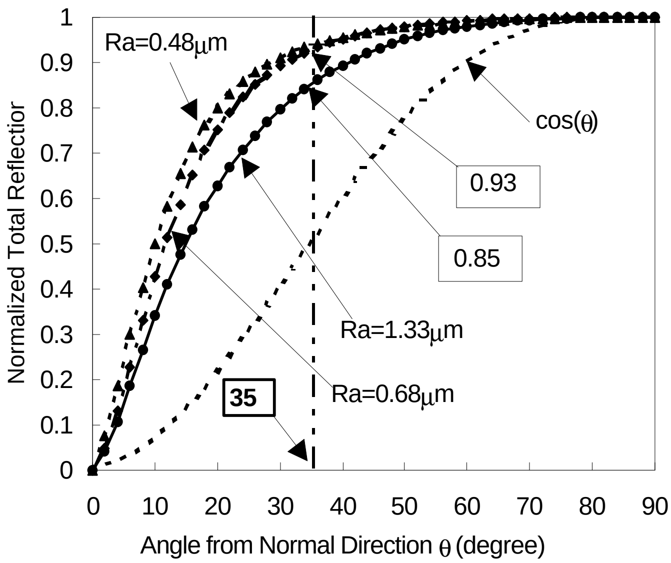

Fig.4 Dependence of normalized total reflection on zenith angle (θ)

3.2 Construction of the new radiation pyrometer

A schematic diagram of the new radiation pyrometer is shown in Fig.5. One light detector measures reflected light intensity from normal to 15 degrees (specular component) and the other one measures reflected light intensity from 15 degrees to 35 degrees (diffuse component). From both measurements we could estimate in-situ emissivity. The light detectors were silicon photodiodes and the light source was an LED. The central wavelength of the LED was 880nm which is almost the same as the effective wavelength of the pyrometer (930nm). The value of the full width at half maximum was 50nm. The LED was driven by a 100Hz square signal. When the LED was on, the sum of the thermal radiation and the reflected light could be measured. When the LED was off, only the thermal radiation from the steel sheet could be measured. Because the light intensity of LED was changed by temperature, we used the referential detector as the standard of light intensity.

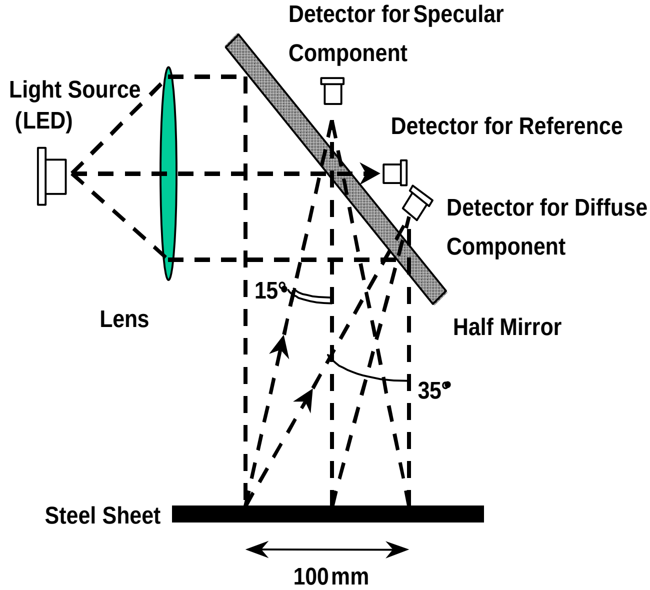

Fig.5 Schematic diagram of a new pyrometer

The light intensity of a diffused component was strongly affected by the tilt angle of the steel sheet. Experimental results are shown in Fig.6. If the steel sheet was tilted only 3 degrees from normal angle, the reflected light intensity changed about 60%. So we tried to measure reflected light at 2 directions. Variation of reflected light decreased within 4.5% when the steel sheet was tilted 3 degrees. For on-line use of the pyrometer we adopted 4 scattered light detectors at right angles, and ignored the effect of steel sheet tilt.

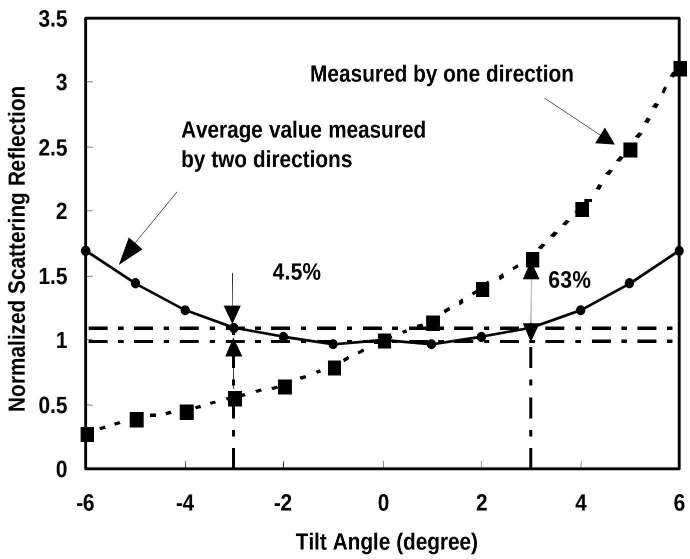

Fig.6 Dependence of normalized scattering reflection on tilt angle

As the new radiation pyrometer was used under the harsh environment of a continuous annealing line, the pyrometer was set in the water cooled pipe, had a window with infrared reflection coating and was purged by nitrogen gas. In order to maintain the performance of the pyrometer, the reference reflectors, one an aluminum sputtered mirror and the other black body paint on a steel sheet are included in the pyrometer. The reflectivity of the references was 0.97 and 0.04.

4. CALIBRATION OF REFLECTANCE MEASUREMENT

4.1 Calibration method

Samples to calibrate reflectance measurement were made by controlled atmosphere as shown in Fig.1. A sample steel sheet was heated under vacuum conditions, and an adequate amount of air was introduced into the furnace. Five samples with different emissivity were made. Emissivity of the samples were from 0.42 without oxidation film to 0.9 with oxidation film. Emissivity was measured at 930nm. With these 5 samples, we used an aluminum sputtered mirror and black body paint on the steel sheet to calibrate the reflectance measurement. Calibration can be done as follows :

$$\text{Reflectance}=C1\times(\text{light intensity of specular component})/(\text{light intensity of reference}) +C2\times(\text{light intensity of diffuse component})/(\text{light intensity of reference}) \quad (3)$$

Step 1 : We used an aluminum sputtered mirror. In this case, C2 was zero. From this measurement, C1 was determined.

Step 2 : From experimental data of another 6 samples, we estimated C2 using statistical analysis, a linear regression.

Step 3 : Emissivity was calculated by equation (1).

Table 1 Results of emissivity estimation

True emissivity	Estimated emissivity	Estimated error (%)
0.42	0.423	2.9
0.59	0.55	6.8
0.7	0.657	6.2
0.85	0.79	-7.1
0.9	0.85	-5.5
0.96	0.96	0

Calibration results are shown in Table 1. Maximum emissivity errors between true emissivity measured by the thermocouple and radiometer and estimated emissivity obtained from reflectance were ±7%. This error is acceptable for on-line process measurement.

4.2 Evaluation of calibration accuracy

In order to evaluate the calibration accuracy of reflectance, we use 18 samples whose emissivity and surface roughness were different. Emissivity ranged from 0.37 to 0.91 and surface roughness(Ra) ranged from 0.9 to 1.44ìm. Maximum value of surface roughness was greater than the one of usual cold rolled steel sheet which is annealed in a continuous annealing line. Experimental results are shown in Fig.7. The standard deviation of estimated emissivity error between true emissivity and estimated emissivity from measured reflectance was 6.5%. Temperature measurement error due to estimated emissivity error was calculated from output characteristics of the pyrometer. The standard deviation of estimated temperature measurement error was less than 0.5% of absolute temperature for temperature ranged from 700 to 900°C. For example at 700°C estimated temperature measurement error was about 4°C.

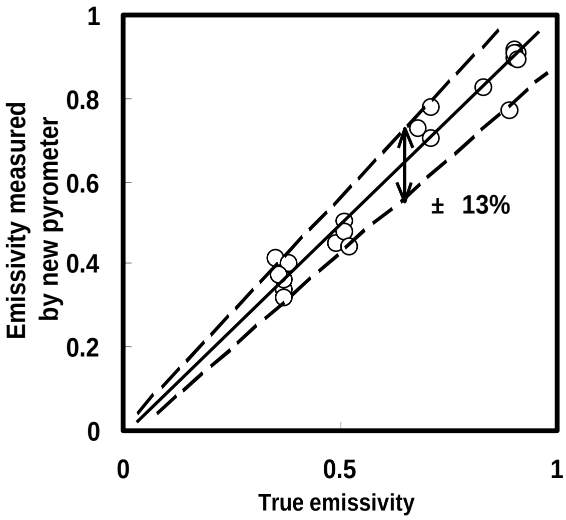

Fig.7 Correlation between true emissivity and emissivity measured by new pyrometer

5 TEMPERATURE MEASUREMENT ERROR

5.1 Results of laboratory experiment

The new radiation pyrometer was examined in a laboratory furnace to evaluate temperature measurement error. Cold rolled steel sheet was heated to about 700°C in the controlled atmosphere furnace, and was oxidized by a small amount of air. The temperature of the cold rolled steel sheet measured by the new radiation pyrometer was compared with the temperature measured by a thermocouple welded onto the steel sheet. Experimental results are shown in Fig.8. Emissivity varied from 0.4 to 0.74. The two temperature values are almost same and the standard deviation of temperature measurement error by the new radiation pyrometer was about 4°C. This value agreed with estimated temperature error from reflectance measurement error.

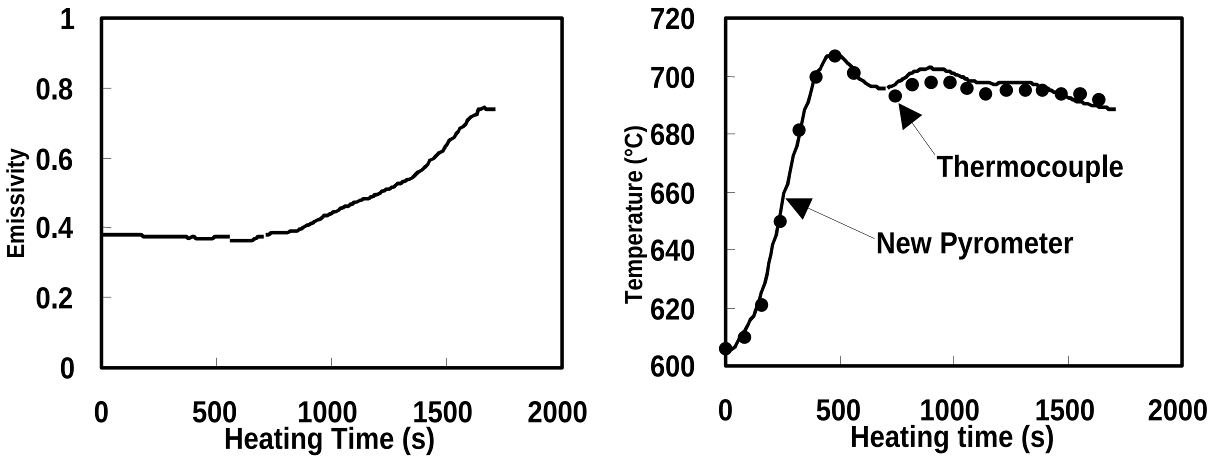

Fig.8 Temperature and emissivity data during oxidation in laboratory experiment

5.2 On-line temperature measurement

The new radiation pyrometer was tested on a continuous annealing line. The pyrometer was set with a water cooled radiation shield at the outlet of the heating section near the conventional radiation pyrometer with fixed value emissivity compensation. The temperature of the cold rolled steel sheet was measured by a thermocouple. The thermocouple was firmly attached to the cold rolled steel sheet by a heat-resistant wheel. For this test the line was operated in oxidation conditions. Experimental results are shown in Fig.9.

The temperature of the new radiation pyrometer coincided with the temperature of the thermocouple within ±10°C from 600°C to 850°C. But the temperature of the conventional radiation pyrometer differed about 70~90 degrees around 650°C. At this point cold rolled steel sheet was oxidized and emissivity varied from 0.4 to 0.9.

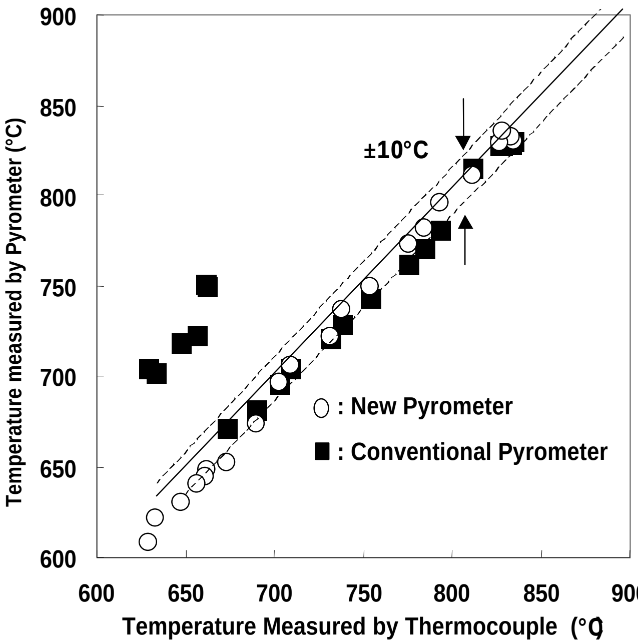

Fig.9 Comparison of temperature accuracy between new pyrometer and conventional pyrometer

6 CONCLUSION

Emissivity of metal sheets was drastically changed and its behavior was very complex in the oxidation process. Therefore, real-time emissivity compensation methods are necessary in order to measure temperature accurately using a radiation pyrometer. We proposed a new type of Pyrometer using the Information of Reflectance (PIR) for steel sheets and good results were obtained on a continuous annealing line.

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