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Effect of surface oxidization on the spectral emissivity of steel 304 at the elevated temperature in air

Deheng Shi *, Fenghui Zou, Shuai Wang, Zunlue Zhu, Jinfeng Sun

College of Physics and Electronic Engineering, Henan Normal University, Xinxiang 453007, China

HIGHLIGHTS

- Resonances of spectral emissivity are observed.
- Variation of spectral emissivity with heating time is studied.
- Variation of spectral emissivity with temperature is evaluated.
- Polynomial functional form is suitable to fit the measurements.
- Contribution to the spectral emissivity by oxidation is mainly from the first 150 min.

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ABSTRACT

Effect of surface oxidization on the spectral emissivity of steel 304 is studied over the temperature range from 830 to 1100 K at 1.5 μm. The experimental setup is composed of three modules: the optical receiving system, the specimen heating and temperature-controlling system, and the signal-controlling and data-computing system. The temperature of steel 304 specimens is measured by averaging the two R-type platinum–rhodium thermocouples. The radiant energy stemming from the surface specimens is received by an InGaAs photodiode detector. The growth law of oxidization film on the surface of steel 304 specimens is observed carefully. The variation of spectral emissivity with the heating-duration time is studied at a given elevated temperature. The dependence of spectral emissivity on the temperature is evaluated at a definite heating-duration time. The interference enhancement of spectral emissivity appears mainly during the initial heating-duration period, in particular at a relatively low elevated temperature. The interference effect between the radiation stemming from the oxidization film on the specimen surface and the radiation coming from the surface of specimens is discussed, which has been affirmed to be responsible for the interference enhancement of spectral emissivity. The analytic model between the spectral emissivity of steel 304 specimens and the temperature of specimen surface is evaluated at several definite heating-duration times. The conclusion is derived that the polynomial functional form is very suitable for fitting the experimental results obtained at a given heating-duration time at 830–1100 K.

1. Introduction

With its inherent attributes of high strength, corrosion resistance, and full recyclability, steel has been affirmed to have extensive applications in every type of industry. Examples include numerous parts of aircraft and satellite, window frames, mobile frames, engine block, and body panels. All these applications need high-quality steel materials. As we know, most processes in steel production such as forging, extrusion, cold rolling, and hot rolling are highly temperature-dependent, and the precise determination of temperature has a strong bearing on both the process control and the final product quality. However, many of these processes preclude direct physical contact of a temperature probe with the target surface. As a consequence of this, only the radiation thermometer can be used as a powerful temperature measurement tool in these industrial situations.

However, we must obtain the adequate knowledge of spectral emissivity of a target before we use a radiation thermometer to determine accurately its temperature. For example, to measure accurately the surface temperature of steel in production, we need to know the relationship between the spectral emissivity and the

* Corresponding author. Tel./fax: +86 373 3326375.
E-mail address: scattering@sina.com.cn (D. Shi).

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temperature for a single-wavelength thermometry, and we also require some prior knowledge between the spectral emissivity and the wavelength and temperature for a colorimetric thermometry. Unfortunately, the spectral emissivity of a target depends on a number of parameters, such as wavelength and temperature, and sometimes quickly varies with these parameters [1–4]. At some cases, even for a given wavelength and a given temperature, the spectral emissivity may also be greatly changed with the surface roughness [2,5–7], emission angle [8,9] and oxidization film on its surface [8–13]. As we know, steel is exposed in air at an elevated temperature in the whole production process. Surface oxidization is always traveling through the whole period of manufacture. As a consequence of this, to measure the temperature of steel surface in production as accurately as possible, we must clarify the effect of surface oxidization on the variation of spectral emissivity with the temperature in air.

Some previous experimental work has studied the effect of surface oxidization on the spectral emissivity of various steel materials. For example, Furukawa and Iuchi [8] measured the spectral emissivity of steel in the oxidizing surroundings. Campo et al. [9] studied the spectral emissivity of stainless steel in a controlled environment. They [8,9] in brief discussed the effect of surface oxidation on the spectral emissivity. Kobayashi et al. [10] in brief studied the effect of surface oxidization on the spectral emissivity of steel in vacuum and oxidizing environments, and obtained some interesting results. Summarizing the measurements reported in the literature, we find that previous experimental work only qualitatively evaluated the effect of surface oxidization on the spectral emissivity of steel. Very few quantitative spectral emissivity results can be available. More importantly, very few analytic models between the spectral emissivity and the temperature in air have been reported in the past several decades, in particular at an elevated temperature. For this reason, some experimental work should be performed so as to clarify the effect of surface oxidization on the spectral emissivity, and to obtain the accurate analytic models in air, prior to the practical applications of a radiation thermometry.

The aim of the present work is to extend the spectral emissivity knowledge of steel 304 in air at an elevated temperature since the analytic models between the spectral emissivity and the temperature are very few. For this reason, two kinds of relationships between the spectral emissivity of steel 304 and the temperature are studied in detail in air. One is the variation of spectral emissivity with the heating-duration time at a definite elevated temperature. The other is the variation of spectral emissivity with the temperature at a given heating-duration time.

In the next section, the measurement principle of experimental setup is briefly outlined, and the experimental procedure is briefly introduced. In Section 3, the measurements of spectral emissivity of steel 304 specimens are reported, and some necessary discussion is performed. And in Section 4, the concluding remarks are given.

2. Experiment

2.1. Measurement principle

We first briefly describe the configuration of this experimental setup so that we can conveniently introduce its measurement principle. This setup mainly consists of three modules. The first one is the optical receiving system. The second one is the specimen heating and temperature-controlling system. The last one is the signal-controlling and data-computing system.

The positioning method of thermocouples, detector and specimens is demonstrated in Fig. 1. In experiment, the specimen is heated to a given temperature by an eddy current heater. The specimen temperature is monitored by two thermocouples, which are

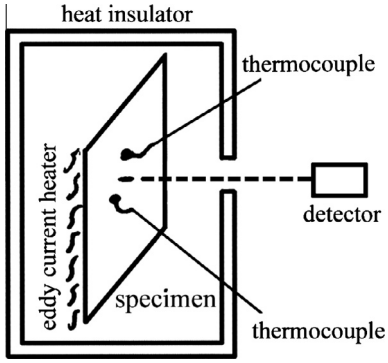

Fig. 1. Schematic diagram of positioning method of thermocouples, detector and specimens.

symmetrically welded in the front surface of specimen near the measuring area viewed by an InGaAs photodiode detector. The optical receiving system works at the wavelength of 1.5 μm with the bandwidth of about 20 nm. It should be pointed out that the detector must be perpendicular to the specimen surface as accurately as possible so that we can measure the normal spectral emissivity as accurately as possible.

Suppose that the radiant energy coming from the surface of steel 304 specimens is P_1, and the radiant energy stemming from a perfect blackbody emitter is P_2 at the same wavelength λ and at the same temperature T. Then, the radiant energy P_1 stemming from the steel specimens can be written as

$$P_1 = \frac{\pi^2}{4}\left(\frac{D}{f'}\right)^2 \tau_0 A \int_{\lambda_1}^{\lambda_2} \tau_\lambda 2\pi hc^2 \varepsilon_\lambda \lambda^{-5} \left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]^{-1} d\lambda, \quad (1)$$

where D and f' are the aperture diameter and focal length of optical receiving system, respectively. τ_0 is the propagation coefficient of the atmosphere, which has included the effect of absorption by the CO_2 gas and moisture present in the environment on the signal from the surface and substrate to the optical detector. A is the area of sensitive unit of detector. λ_1 and λ_2 are the spectral limits of optical receiving system used to select the spectral band. τ_λ is the total transmissivity of optical receiving system.

The bandwidth $\Delta\lambda$ of optical receiving system is only 20 nm, which is very narrow. Within such a narrow bandwidth, we can approximately regard τ_λ as a constant, although τ_λ is never constant between λ_1 and λ_2 for a real infrared thermometer. Including these considerations into Eq. (1) and by setting

$$C = \frac{\pi^3}{2}\left(\frac{D}{f'}\right)^2 \tau_0 A \tau_\lambda hc^2 \lambda^{-5} \Delta\lambda, \quad (2)$$

we obtain

$$P_1 = C \cdot \varepsilon_\lambda \left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]^{-1}. \quad (3)$$

Similarly, the radiant energy P_2 stemming from a perfect blackbody emitter at the same wavelength λ and at the same temperature T can be written as

$$P_2 = C \cdot \left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]^{-1}. \quad (4)$$

Then, we can determine the spectral emissivity ε_λ by

$$\varepsilon_\lambda = \frac{P_1}{P_2}. \quad (5)$$

In Eq. (5), P_2 is obtained by prior measurements at some separate temperatures, and is stored in the control computer. P_2 between the two adjacent storing radiant values can be accurately