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Modeling the effect of surface oxidation on the normal spectral emissivity of steel 316L at 1.5 μm over the temperatures ranging from 800 to 1100 K in air

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HIGHLIGHTS

- Resonances of normal emissivity are observed.
- Variation of normal emissivity with temperature is discussed.
- Variation of normal emissivity with heating time is studied.
- Analytical model to fit the measurements has been found.
- Contribution to the normal emissivity by oxidation is mainly from the first 200 min.

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ABSTRACT

The effect of surface oxidation on the normal spectral emissivity of steel 316L has been modeled at 800–1100 K in air at 1.5 μm. The radiance from the specimen is received by an InGaAs photodiode detector. The specimen temperature is obtained by averaging the two platinum–rhodium thermocouples, which are welded in the front surface of specimen near the measuring area viewed by the detector. The normal spectral emissivity of steel 316L specimens is measured in air over a 6-h heating period at a definite temperature. The strong oscillations of normal spectral emissivity have been observed and discussed, which are affirmed to be connected with the thickness of oxidization layer on the specimen surface, and formed by the interference effect between the radiation stemming from the oxidization layer and the radiation from the substrate. At a given temperature, the variation of normal spectral emissivity with the heating time abides by an analytical model. And at a definite heating time, the variation of normal spectral emissivity with the temperature also follows the same functional form. The uncertainty of normal spectral emissivity contributed only by the surface oxidation is about 3.7–15.0%, and the corresponding uncertainty of temperature yielded only by the surface oxidization is about 4.1–11.7 K. The conclusion is that the analytic model used here can well reproduce the behaviors of normal spectral emissivity except for the strong oscillation occurring in the initial heating period.

1. Introduction

Various kinds of steels are undeniably the most important metals in current industry. The inherent attributes of high strength and hardness, ease of fabrication, fire resistance, impact resistance, corrosion resistance and recyclability have made various kinds of steels become choice for applications ranging from household window frames to structural members in commercial aircraft and military. It is well-known that many processes in steel manufacture usually encounter very high temperature, and are highly temperature-dependent. It is no exaggeration to say that we must accurately measure and control the temperature of various kinds of steels in their production processes if we want to attain the desired mechanical properties, ensure the product quality and reproducibility, and reduce the cost.

Two kinds of temperature measurement approaches can accurately determine the temperature of steel. One is the direct physical contact of a temperature probe with the steel surface. The other is the radiation thermometry, which needs some prior spectral knowledge of steels. However, some processes in steel production, such as extruding, forging, cold rolling, and hot rolling, preclude

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direct physical contact of a temperature probe with the fast-moving steel surface. Here, the radiation thermometry becomes an excellent candidate to monitor the temperature of steel surface without contact and quickly.

Radiation thermometry, however, involves a serious problem concerning the spectral emissivity when it is used to measure the temperature of steels. That is, if the spectral emissivity varies, the true temperature of steel surface cannot be accurately evaluated. As we know, various steels in production usually encounter an elevated temperature, and their spectral emissivity may greatly change with the growth of the oxide layer on their surfaces when they are heated in air for a long time. Therefore, it is important to clarify the variation of spectral emissivity with the heating time for various steels, prior to practical applications of a radiation thermometry.

In recent years, there has been an amount of theoretical and experimental work [1–10], in which the variation of spectral emissivity with the growth of the oxide layer on the steel surface was studied. Kobayashi et al. [1] in 1999 developed an experimental setup to measure the time variations of spectral emissivity at wavelengths ranging from 0.55 to 5.3 μm over the temperatures from 1053 to 1473 K. For the steels, they only qualitatively evaluated the dependence of spectral emissivity on the heating time for the painted sheets of cold-rolled steel at 0.9 μm in the oxidizing environment at 1073 and 1273 K, respectively. Furukawa and Iuchi [2] in 2000 designed an experimental setup to measure the normal and directional spectral emissivity in the controlled environment at the wavelengths from visible to 10 μm. For the steels, Furukawa and Iuchi [2] only qualitatively evaluated the variation of spectral emissivity of cold-rolled steel sheet with the heating time at 1.35, 1.55 and 2.2 μm and at 873 K in the oxidizing environment. Iuchi [3] in 2003 modeled the behaviors of directional and polarized spectral emissivity of various metals during the growth of oxide layer. For the steel, they simulated the spectral emissivity changes at 1.3 and 1.5 μm of cold-rolled steel during the growth of oxide layer. Some new phenomena were observed. Campo et al. [4] in 2006 presented a new experimental apparatus for the directional spectral emissivity measurements in a controlled atmosphere over the wavelengths ranging from 1.28 to 25 μm and the temperature ranging from ambient to 1050 K. Using this apparatus, they qualitatively evaluated the variation of spectral emissivity of Armco iron with the wavelength at the different heating times. Pujana et al. [5] in 2007 evaluated the variation of spectral emissivity of steel 42CrMo4 with the heating time at 2.12, 4.0 and 8.0 μm and at 959 and 1073 K in a controlled atmosphere. They observed that the spectral emissivity appreciably increased during the oxidization, and thought that the oscillatory behavior of spectral emissivity tended to disappear when the oxidation scale is optically thick.

Very recently, Wen and Lu [6] in 2010 used the multispectral radiation thermometry to study the spectral emissivity for the stainless steels (AISI 420 and AISI 630), hot-work tool steels (AISI H10 and AISI H13), and cold-work tool steels (AISI A2 and AISI A6) over the wavelengths ranging from 2.91 to 4.13 μm at the temperatures of 700, 800, and 900 K. However, they did not evaluate the effect of heating time on the spectral emissivity. Wen [7] in 2010 qualitatively investigated the effect of heating time on the spectral emissivity for six kinds of steels at 3.51 μm and 900 K. They found that the steel alloys with higher spectral emissivity values had larger change in spectral emissivity during the initial three-hour heating time. Reschab et al. [8] in 2011 presented the spectral emissivity at melting and in the liquid state of the highly alloyed steel HS2-9-1-8 at 684.5 nm, and found that the trend of spectral emissivity abides linearly. However, they did not either evaluate the effect of heating time on the spectral emissivity. Wen [9] in 2011 measured the spectral emissivity of a variety of steels at 700, 800, and 900 K over the wavelength ranging from 2.0 to 4.8 μm, and in brief studied the effect of heating time on the spectral emissivity. Only qualitative discussion was made in his work [9]. Our group [10] in 2013 studied the effect of surface oxidization on the spectral emissivity of SPHC steel specimens over the temperatures ranging from 800 to 1000 K at 1.5 μm. Some novel phenomena were observed. However, only the qualitative discussion was given at that work [10].

Summarizing the experimental and theoretical results available in the literature [1–10], we have found the following. Firstly, as seen in the literature, the surface oxidization can bring about great effect on the spectral emissivity of various kinds of steels. How many are the measurement uncertainties of spectral emissivity and temperature contributed only by the surface oxidization? This question has not been clearly answered by any previous work. Secondly, although almost all the work mentioned here has studied the effect of surface oxidization on the spectral emissivity of various steels, very few analytic models can be found between the spectral emissivity and the temperature or heating time. Does the effect of surface oxidation on the spectral emissivity of steel follow the same rule at a given heating time or at a given temperature? And finally, the strong oscillation of spectral emissivity of steels was observed in previous experimental work, whereas the details including their change rules have not been discussed so far. For this reason, we think that further experimental work should be made so as to clarify these problems, in particular at an elevated temperature in air for a long time.

To clarify the problems mentioned above, very recently, we have investigated the effect of surface oxidization on the normal spectral emissivity of steel 302 and steel 201 over the temperatures ranging from 800 to 1100 K in air at 1.5 μm [11,12]. Some interesting phenomena were observed, and some discussion was made. In this work, we will further investigate such effect of surface oxidation on the normal spectral emissivity at an elevated temperature in air, and explore the corresponding analytical model reproducing well the behaviors of normal spectral emissivity.

We select the steel 316L as the target of this paper. The reason is that no spectral emissivity has been reported about this kind of steel in available literature, let alone the effect of heating time on its spectral emissivity. In this paper, only the normal spectral emissivity is studied. In the next section, the measurement principle and experimental procedure of the experimental setup are briefly described. In Section 3, the normal spectral emissivity of steel 316L specimens are measured and reported over the temperature range from 800 to 1100 K at 1.5 μm. Some necessary discussion is made. And in Section 4, the concluding remarks are given.

2. Experiment

2.1. Measurement principle

To outline conveniently the measurement principle, in Fig. 1, we depict the schematic diagram of positioning method about the two thermocouples, one detector and one piece of specimen. In this experimental setup, the specimen is heated up to a given temperature by an eddy current heater. The specimen temperature is monitored by the two thermocouples, which are symmetrically welded in the front surface of specimens near the measuring area viewed by an InGaAs photodiode detector. It should be pointed out that the detector used in this experimental setup must be perpendicular to the specimen surface as accurately as possible so that we can measure the normal spectral emissivity as accurately as possible.

The radiance coming from a real surface is forever smaller than that from a perfect blackbody emitter at the same wavelength λ