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Research Paper

Investigation of the effects of Ni-based alloy DZ125 on the normal spectral emissivity during oxidation

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HIGHLIGHTS

- Emissivity of Ni-based alloy at high temperatures is measured during oxidation.
- The emissivity increases as temperature increases and wavelength decreases.
- The oscillations of the emissivity occur due to interference effect.
- Fitting models are developed to study the change of the emissivity quantitatively.

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ABSTRACT

The normal spectral emissivity of Ni-based alloy DZ125 during oxidation is experimentally measured at 810, 916 and 998 °C for 12 h in air over the wavelength from 1.35 to 2.35 μm. The combined standard uncertainty of the normal spectral emissivity is less than 3%. The oscillations of the emissivity and the effects of oxidation temperature, heating time and wavelength on the emissivity are investigated. The oscillations of the emissivity are formed by the interference effect of radiation between the surfaces of the substrate and the oxidation film. The interferential extremums of the emissivity shift towards larger wavelengths as the oxidation process proceeds. The results show that the normal spectral emissivity increases basically with increasing temperature and decreasing wavelength except for the occurrence of the oscillations of the emissivity. The normal spectral emissivity increases rapidly at the initial heating time, and the change of emissivity becomes slow when the oxidation is going to be saturated. Besides, the emissivity fitting models versus heating time and wavelength are established, which fit the experiment data very well. The emissivity relative errors of the fitting models are less than 3%.

1. Introduction

Turbine blades are used in the severe environment, such as high temperature and high pressure. What is more, rotor blades are under the high-speed revolution situation. Thus, turbine blades are one of the most vulnerable parts in the aero-engine. In order to improve the engine efficiency, the turbine inlet temperature (TIT) increases as high as possible. It is necessary to measure the accurate temperature of the turbine blades real-timely during working process to protect turbine blades from over temperature exposure. However, the methods of contact temperature measurement are undesirable in measuring the blades temperature because of its short lifetime at the severe environment [1,2]. A more accurate, nondestructive and easy-using non-contact radiation thermometry is needed. Radiation thermometry can be divided into three categories according to their principles: spectral radiation thermometry (SRT), dual-wavelength radiation thermometry (DWRT) and multispectral radiation thermometry (MRT). The exact spectral emissivity of an object must be known if the SRT is used to measure its temperature accurately. The prior knowledge of the relationship between the spectral emissivity and wavelengths is acquired when the DWRT or MRT is used to evaluate the accurate temperature of an object. However, the emissivity is influenced by a large number of variables, such as alloy composition, temperature, wavelength, surface characteristics (oxidation and roughness), heating time and process conditions [3]. In high-temperature aero-engine environment, the alloy of turbine blades tends to be oxidized easily. The change of alloy's emissivity will cause large errors in radiation thermometry. Therefore, it is meaningful to study the change regularity of the emissivity of Ni-based alloys for accurate temperature measurement of the blades. The

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precise emissivity of turbine blades can also be used to calculate accurate temperature field of the turbine, which radiation is taken into account.

In recent years, the emissivity of various metals and alloys with oxidation has been researched experimentally and theoretically. Brannon and Goldstei [4] investigated the variation of total normal emittance as a function of oxide thickness for Al-Al_2O_3 and Cu-CuO systems. The total emittance increased greatly as the oxide layer thickness increased. Mehling et al. [5] measured the infrared emissivity of various metals as a function of wavelength and angle of emission. They found that materials oxidation would result in a higher emissivity and an almost isotropic emissivity distribution. Kobayashi et al. [6] developed a system to measure the normal emissivity with time in vacuum and oxidizing environments, and wavelength and temperature range were 0.55–5.3 μm and 780–1200 °C, respectively. A database of the normal spectral emissivity for thirty kinds of pure metals and alloys was built [7]. Furukawa and Iuchi [8] developed an apparatus to measure the spectral and directional emissivity in the controlled environment over the temperatures from room temperature to 1023 K. Then Iuchi [9] modeled the behaviors of directional and the polarized emissivity of metals during the growth of oxide films, which corresponded well with experimental results. Greene et al. [10] measured the total hemispherical emissivity of Inconel 718 for both unoxidized and oxidized samples as a function of sample temperature. They found that the oxidized samples showed a significant increase in the emissivity over the unoxidized samples. The sample infrared emissivity as a function of the oxidation time for temperature between 450 and 800 °C was measured by del Campo et al. [11] to study the WC-based carbides oxidation kinetics. They [12] measured the emissivity of three Ni and Co based alloys to analyzed the effects of temperature, wavelength, emission angle and oxidation. They found the emissivity decreased with increasing wavelength independent of temperature and the oxidized samples had a higher emissivity. Fu et al. [13] studied the effects of substrate oxidation state on the total hemispherical emissivity of iron-based alloys by calorimetric technique. Wen et al. tested the spectral emissivity of aluminum [14] and steel [15,16] at several hundred Kelvin degree during oxidation and investigated the effects of wavelength, temperature, alloy composition and heating time on the spectral emissivity qualitatively. Shi et al. explored the relationships between heating time and the emissivity of straight carbon steel [17], aluminum [18], steel [19] and red copper [20] during oxidation at high temperatures in air, and they developed analytical models to simulate the emissivity varied with time.

The oscillatory behavior of the emissivity during oxidation is peculiar. Kobayashi et al. [6,7] and del Campo et al. [11,21,22] observed several strong emissivity oscillations in the experiment. Only one obvious oscillation was observed by Furukawa and Iuchi [8], Wen [15,16] and Shi et al. [19]. However, Brannon and Goldstei [4], Greene [10], Wen et al. [14,23] did not found out any oscillations of the spectral emissivity. If the oscillations of the emissivity occurred, it would disappear when the oxidation film was optically thick enough. All the emissivity finally approached to fixed values after the saturation of the oxidation.

In previous works, only Shi et al. [17–20] did the quantitative analysis of the emissivity during oxidation, but their analysis was confined to a single wavelength. Other researchers only did the qualitative analysis and did not give a model. What's more, few researchers have studied the emissivity of Ni-based alloys during oxidation, and most measured sample temperature was under 700 °C. The main purposes of the paper are to study the quantitative change regularity of the normal spectral emissivity of Ni-based alloy DZ125 during oxidation in air at different high temperatures and to model the emissivity versus heating time and wavelength.

2. Experiment

2.1. Measurement principle

As known to all, the maximum possible thermal radiative intensity at a given temperature is emitted by a blackbody, and the emissivity is defined by [24]

$$\varepsilon_{\lambda,\theta}(\lambda,T,\theta,\phi) \equiv \frac{I_{\lambda,e}(\lambda,T,\theta,\phi)}{I_{\lambda,b}(\lambda,T)} \tag{1}$$

where $I_{\lambda,e}$ and $I_{\lambda,b}$ are the radiative intensity coming from a real surface and the perfect blackbody at the same temperature and wavelength, respectively. θ and ϕ are the emitting zenith angle and azimuth angle, respectively. And the radiative intensity of the blackbody can be obtained from the Planck distribution

$$I_{\lambda,b}(\lambda,T) = \frac{C_1/\pi}{\lambda^5\{\exp[C_2/(\lambda T)]-1\}} \tag{2}$$

where $C_1 = 2\pi hc_0^2$ and $C_2 = hc_0/k$.

The sample spectral intensity $I_{\lambda,meas}$ measured by a Fourier transform infrared spectroscope (FTIR) is composed of four components [14],

$$I_{\lambda,meas} = I_{\lambda,e}(\lambda,T,\theta,\phi) + I_{\lambda,sur} + I_e + I_\beta \tag{3}$$

where $I_{\lambda,e}$ is the self-emitted intensity from the sample surface, $I_{\lambda,sur}$ is the intensity from the surrounding irradiation reflected by the sample surface, I_e is the sample intensity emitted by the sample, which is then reflected by the surrounding and the sample itself, and I_β is the intensity of atmospheric scattering and absorption (H_2O, CO_2, dust particles, etc.). Because the radiation exchange between the sample and the surrounding is between a small and a large enclosure, the term I_e is neglected due to the blackbody assumption of the surrounding. In the absence of atmospheric absorption or emission, then the term I_β is also negligible. Therefore, the measured intensity of an opaque sample surface, $I_{\lambda,meas}$, can be simplified as

$$I_{\lambda,meas} \cong I_{\lambda,e}(\lambda,T) + I_{\lambda,sur} = \varepsilon_\lambda I_{\lambda,b}(\lambda,T) + I_{\lambda,sur} \tag{4}$$

The response of the FTIR to the incident radiative intensity is approximatively linear. The output S of the FTIR of the measured intensity can be described as

$$S(\lambda,T) = R(\lambda)\cdot[G_1(\lambda)\cdot I_\lambda(\lambda,T) + G_2(\lambda)\cdot I_{\lambda,sur} + I_0] \tag{5}$$

where I_0 is the radiative intensity emitted by the FTIR. $G_1(\lambda)$ and $G_2(\lambda)$ are the geometrical factors of the target and the surrounding, respectively. $R(\lambda)$ is the response function of the FTIR. $G(\lambda)$ and $R(\lambda)$ only correlate to the wavelength and are temperature-independent. Hence, the normal spectral emissivity of the sample at temperature T and wavelength λ can be derived as

$$\varepsilon_\lambda = \frac{I_{\lambda,e}(\lambda,T)}{I_{\lambda,b}(\lambda,T)} = \frac{(S_s - S_0)\cdot[I_{\lambda,b2}(\lambda,T_{b2}) - I_{\lambda,b1}(\lambda,T_{b1})]}{I_{\lambda,b}(\lambda,T_s)\cdot(S_{b2}-S_{b1})} \tag{6}$$

where S_{b1} and S_{b2} are the FTIR output of the blackbody at T_{b1} and T_{b2}, respectively. S_s is the FTIR sum output of the sample at T_s, the surrounding and the FTIR, and S_0 is the sum output of the surrounding and the FTIR. When the intensity of the blackbody is measured, the optical path must be the same as that between the detector and the sample. The emissivity can be calculated by Eq. (6).

2.2. Experimental setup

The experimental apparatus used in this paper is shown in Fig. 1. It is primarily comprised of a sample heating assembly and temperature controller, receiver of radiation, FTIR (NIR 2500,