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Normal spectral emissivity measurement on five aeronautical alloys

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ABSTRACT

Aeronautical alloys have a good performance on resisting oxidization, corrosion and fatigue in high temperature environments. Therefore, they are not only widely employed in aero-engine but also in nuclear and petroleum industries. The normal spectral emissivity of five alloys in the wavelength ranging 1–15 μm at moderate and high temperature (400–1200 K) is measured. It is found that the emissivity decreases with the increasing of wavelength and increases when temperature rises. The effects of oxidation and flame treatment process are also studied. The results of the oxidized samples indicate that oxidation can enhance the emissivity significantly and alter the wavelength dependent trend. The results of the flame treatment processed samples show that the impurities and defects caused by the flame treatment process moderately increase the emissivity. The experimental data presented in this paper can be used directly to improve the accuracy of radiation computation and other relevant applications.

1. Introduction

Radiation is an important heat transfer mode for the hot parts of aero-engines, which significantly affects the structure and strength of aircraft parts. To describe the capacity of emitting radiation of a certain material, emissivity is defined by the ratio of the emissive power of the material and blackbody at the same temperature. The emissivity generally varies with wavelength, temperature and surface conditions. Even for the same material, different surface conditions, such as oxidation, contaminate and different surface micromorphology, have considerable effects on it [1]. However, there are limited theories to predict emissivity accurately, especially for the real material surfaces [2–5]. Therefore, measuring emissivity in a certain material with different surface conditions is significant for high fidelity radiation computation and improving the understanding of radiation heat transfer.

Aeronautical alloys are not only widely employed in hot parts of aero-engines but also in nuclear and petroleum industries because of their good performance in resisting oxidization, corrosion and fatigue in high temperature environment. So some researches have already been carried on. Campo investigated the normal and directional emissivity of three kinds of Ni and Co based aeronautical alloys, Inconel 718 (GH169), Rene41 and Haynes 25, on wavelength (2–22 μm), sample temperature (200–650 °C) and emission angle (0–85°). The effects of the following surface conditions, brushed, sandblast, wire-cut EDM and oxidation, on emissivity were taken into consideration [6]. Keller measured the hemispherical emissivity of Inconel 718 in four different surface types from 650 K to 1275 K, and found that the hemispherical emissivity increased with the increase of temperature and oxidation [7]. Greene measured the hemispherical emissivity of Inconel 718 for the as-received sample and oxidized sample [8]. The normal emissivity of two nickel-based superalloys at the melting transition and in the molten state at 684.5 nm was reported [9].

In this paper, the normal emissivity of GH169, K417G, K77, DZ125 and DD5 in the range of 1–15 μm at 400–1200 K has been measured. Almost all radiation is covered in this range, when these alloys are employed. So emissivity acquired in this experiment is applicable. It can be seen that the emissivity of GH169 has been widely studied and the current experiment extents its temperature range. No emissivity data of K417G, K77, DZ125 and DD5 can be found in literature. Thus the experiment results presented in this paper will show the data for the first time. In addition, when these alloys are used in aero-engine, two typical surface conditions, oxidation and heated by flame, are also considered.

2. Experimental

2.1. Samples

Table 1 shows the composition of each alloy in weight percentage. Alloys are machined into disk samples with the dimension

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of 30 mm in diameter and 2 mm in thickness and then polished using sandpaper. Then these samples are washed by acetone to clean the surfaces and then dried in the air. After that, some of them are heated in a high-temperature air muffle furnace at the temperature of 900 °C for 10 h then cooled down to the room temperature in the open air. Some are processed in a kerosene flame for 20 min. So we get three kinds of samples with different surface conditions of each alloy: polished, oxidized and flame treatment processed. These samples can be easily distinguished by their appearance. The polished surfaces are silver-white and shiny. The oxidized surfaces are black and rough. The flame treatment processed surfaces are brown. We measure the roughness of these samples using a conventional roughmeter. Table 2 shows the average roughness (Ra) of each sample. Seen from their appearance, the oxidized samples have the roughest surfaces and the flame treatment processed samples increase not much in roughness. Then a scanning electron microscope (SEM) is used to observe the detail surface micromorphology of each sample. The images in different magnifications are shown in Fig. 1. It can be seen that the polished surfaces are relatively smooth and clean but some tool marks still exist. The oxidized surfaces are covered by continuous oxide films which consist of many cubic crystals. There are some differences between alloys that the films of K417G, DD5 and DZ125 are more uniform than that of GH169 and K77. The flame treatment process introduces some impurities and defects on the surfaces. And X-ray diffraction (XRD) is performed on oxidized and flame treatment processed surfaces to detect products generated. The patterns are displayed in Fig. 2. Analyzing the position and relative intensity of these peaks, we can see that the products on the oxidized samples are almost the same which are Cr_2O_3 in a higher proportion and fewer $NiCrMnO_4$. The XRD results also show that oxides quantity in the film of GH169 and K77 are higher than K417G, DD5 and DZ125, which indicates that K417G, DD5 and DZ125 have a better oxidation resistance than GH169 and K77. It agrees with the oxidized rate of these alloys reported in literature [10]. There is no oxide detected on the flame treatment processed surfaces. Since the diffusion flame consumed most oxygen in the air and the flame treatment processing time is not long enough.

Table 2
Roughness average (Ra) of each sample.

	Ra (μm)				
	GH169	K417G	K77	DD5	DZ125
Polished	0.66	0.44	0.55	0.43	0.52
Oxidized	1.84	1.41	2.13	1.38	1.51
Flame treated	0.78	0.59	0.61	0.52	0.57

2.2. Apparatus and measurements

The normal spectral emissivity of each sample is measured by a high-temperature normal spectral emissivity measurement system, which mainly consists of a FT–IR spectrometer, a sample heating chamber, a blackbody chamber a rotation disk and a vacuum system [11]. The FT–IR spectrometer (Nicolet iS50) rapidly and accurately detects and processes the signals from the sample and blackbody. The heating chamber heats up the sample by a Silicon Nitride plate and the temperature is measured by a *S*-type thermocouple wire with the diameter of 0.5 mm. Temperature is controlled by a PID device with the accuracy of 1 °C. The blackbody (ISDC, IR-564) is used to calibrate the radiometer. When temperature is stable, the rotation disk rotates to ensure the radiation emitted from sample and blackbody transmits through the same optical path successively. The vacuum system evacuates the chamber to 10^{-2} Pa to avoid oxidation and the absorption by CO_2 and vapor during measuring.

Because of the radiation of background, emissivity value can't be obtained by direct division of the radiation signals of the sample and the blackbody. Therefore, a calibration procedure should be done before all measurements. This method involves measuring the output radiation signals of the blackbody at low and high temperatures. A water-cooling system is set at 20 °C to keep temperature of the background. So its radiation can be determined. The uncertainty sources of this system come from the temperature measurement, containing the measurement and the stability of the sample temperature and the blackbody temperature, the blackbody cavity effective emissivity, the none-linearity of FTIR and the noise signal. The uncertainty of the temperature is 0.0121. The blackbody cavity effective emissivity uncertainty is 0.0065 and the uncertainty of FTIR is 0.0043, according to the maximum nonlinearity provided by the manufacturer. Hence, the combined uncertainty of this system is 0.0147 and the expended uncertainty is 0.0294 at the 95% confidence level. More details can be found in Ref. [11].

Since surface stress generated during machine process raise emissivity considerably, this effect should be eliminated before measurement [12]. It is also reported that annealing at high temperature is effective to relieve the stress [13]. Therefore, the polished samples were heated for 1 h at 900 °C in vacuum before experiment. The oxidation and flame treatment process have already severed as a relieving step, therefore, their emittance can be measured directly. After all preparations, the emissivity of each sample is measured from 400 K to 1200 K in the interval of 200 K. Every temperature step is kept for 20 min to ensure thermal equilibrium before the FT-IR begins to acquire the sample and blackbody radiation spectrum.

Table 1
Nominal composition of each alloy in weight percentage.

	C	Cr	Ni	Co	W	Mo	Al	Ti	Fe	Ta	Hf	B	Nb	Mg	Ca
GH169	≤0.08	17.0–21.0	50.0–55.0	≤1.0	–	2.80–3.30	0.30–0.70	0.75–1.15	bal.	–	–	≤0.006	4.75–5.50	≤0.01	≤0.01
K77	0.05–0.09	14.0–15.2	bal.	14.0–16.0	–	3.9–4.5	4.0–4.6	3.0–3.7	≤0.5	–	–	0.012–0.20	2.5–3.3	≤0.003	–
K417G	0.13–0.22	8.50–9.50	bal.	9.0–11.0	–	2.50–3.50	4.80–5.70	4.10–4.70	≤1.0	–	–	0.012–0.024	–	–	–
DZ125	0.07–0.12	8.4–9.4	bal.	9.4–10.5	6.5–7.5	1.5–2.5	4.8–5.4	0.7–1.2	≤0.30	3.6–4.1	1.2–1.8	0.01–0.02	–	–	–
DD5	0.05	7	bal.	7.5	5	1.5	6.2	–	≤0.30	6.5	0.15	–	1.2	–	–

	Re	Zr	Si	Mn	S	P	Ag	Pb	Bi	As	Sn	Sb	V	Cu
GH169	–	–	≤0.35	≤0.35	≤0.015	0.015	–	≤0.0005	–	–	–	–	–	≤0.30
K77	–	≤0.04	≤0.20	≤0.20	≤0.015	≤0.0005	≤0.0005	≤0.00005	–	–	–	≤0.10	≤0.1	
K417G	–	0.05–0.09	≤0.20	≤0.20	≤0.010	≤0.015	–	≤0.0005	≤0.0001	≤0.005	≤0.002	≤0.001	0.60–0.90	–
DZ125	–	≤0.08	≤0.15	≤0.15	≤0.01	0.01	≤0.0005	≤0.01	≤0.00005	≤0.001	≤0.001	≤0.001	–	–
DD5	3	–	≤0.20	≤0.15	≤0.004	≤0.018	≤0.005	≤0.0005	≤0.00005	≤0.001	≤0.001	≤0.001	– ≤0.1	