Acknowledgments

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Normal Spectral Emittance Data for Thoriated Tungsten, Rhenium Alloys

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Introduction

THERE are many applications, especially in space-based power conversion systems, where high-temperature data is lacking. In an attempt to contribute to the understanding of the radiative properties of superalloys such as thoriated tungsten, rhenium alloys, the "integral method" employing an accurate photon-counting pyrometer has been used to evaluate the variation of normal spectral (0.535-μm) emittance of these alloys, with temperature as well as alloying content. The results of the experiments conducted on five thoriated (1 Mol. % ThO_2) tungsten, rhenium alloys with up to 30 at.% of rhenium revealed that the spectral emittance decreased with temperature and fluctuated with rhenium content in the temperature range of 1300 to 2300 K.

The accurate measurement of elevated temperatures was recorded by Storms and Mueller,[1] who constructed the photon-counting pyrometer capable of measuring temperatures within 1 K of the International Practical Temperature Scale. The photon-counting pyrometer was later used by Bice and Jacobson[2] to obtain emittance data at high temperatures for refractory metals such as hafnium, iridium, molybdenum, niobium, ruthenium, and tantalum. Petrov et al.,[3] determined the total emittance of molybdenum and found that it increased with an increase in temperature. The effect of change in emittance with temperature for different wavelengths of radiation was well demonstrated by Gubareff et al.,[4] who determined the existence of a certain wavelength (0.75 μm) below which emittance decreases with temperature and above which the emittance increases with temperature. This was later confirmed by Sadykov.[5]

In the photon-counting pyrometer, an interference filter allows the light energy of a particular wavelength (0.535 μm) to pass through a 0.1-mm aperture in a nickel mirror and strike the sensor in the photomultiplier tube. A photocathode sensor detects the incident radiation and converts the energy pulses to current pulses that are amplified by the discriminator-amplifier, and the timer-counter counts the current pulses per unit time, simultaneously displaying the frequency of pulses. This frequency is recorded by a thermal printer, and the recorded data is eventually converted to temperature.

The photomultiplier tube in the photon counter was tested at different threshold and excitation voltages, and the frequencies were recorded to generate a frequency-voltage plot. The plot evened out at 1.4 kV, so the tube was operated at this voltage to obtain a linear response in the expected operating temperature range. Calibration is simple, requiring the use of a single-known temperature, a variable [but an uncalibrated] source of radiation and a value for the wavelength at the transmission maximum of the interference filter. As we were interested in temperatures below 2500 K, the counter was calibrated using the melting point of copper.

The normal spectral emittance was eventually evaluated as a function of the surface and hohlraum temperatures and the pyrometer effective wavelength according to the relation

$$\epsilon_\lambda = \exp[C_c(T_s - T_h)]/\lambda T_h T_s \quad (1)$$

where C_2 is Planck's (second) constant, λ is the pyrometer effective wavelength, and T_s, T_h are the temperatures of the surface and the hohlraum respectively, after correcting for the dead time of the counting circuits and the light attenuation factors for the various filters.

Sample Preparation and Experimental Procedure

The sample, which was heated by electron bombardment, was in the form of a disk 6.35 mm in diameter and 2.54 mm thick. Electrical discharge machining was used to drill a hohlraum with a length of 7.5 mm and a diameter of 0.75 mm in the radial direction. The repeatability of the fabrication of the hohlraum for the different samples was within 4%, maintaining a length-to-diameter ratio of greater than 9:1 in all cases. The region around the hohlraum was polished with 240-grit Carborundum wet/dry paper to provide a flat surface, the emittance of which was to be evaluated. The sample was spot-welded to a tantalum holder and mounted inside the bell jar for experimentation.

Each of the five samples was tested in a water-cooled, diffusion-pumped vacuum system with a vacuum of at least 6×10^{-6} Torr. The sample was heated till the required temperature was attained and maintained at that temperature for one hour, during which frequency measurements were

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recorded. At the end of this period, the pyrometer was moved to focus on the polished region around the hohlraum and the frequency recorded. The sample was then cooled, its surface photographed, and the entire procedure repeated at a higher temperature. The frequencies that were recorded were then converted to surface and hohlraum temperatures from which the emittance was evaluated.

Results and Discussion

The normal spectral emittance values of the various thoriated tungsten, rhenium alloys were plotted as a function of temperature (Fig. 1) and alloying content (Fig. 2). Emittance is a strong function of the pyrometer effective wavelength. As a result, it would be inappropriate to compare the values obtained in this investigation with those of other investigators unless the pyrometer effective wavelength used was the same in all cases. Total emittance values could be compared, but in order to obtain total emittance as a function of temperature, it would be necessary to accumulate more information on spectral emittance by conducting similar experiments with interference filters (other than for 0.535 μm) for different wavelengths. This would involve individual calibration for each interference filter and considerable experimentation before the limited spectral data could be extrapolated to total emittance. In addition to the pyrometric effective wavelength, the type of material and the nature of the surface being investigated are factors contributing to changes in emittance values. General comparisons have been made to confirm and establish the trends expected in the context of the applications for which the tests were intended.

The primary observation in Fig. 1 is that the normal spectral (0.535-μm) emittance decreases with temperature as indicated by Gubareff et al.[4] Micrographs of the surfaces tested at elevated temperatures revealed the formation of polyhedral grains for some of the low-rhenium content alloys. This is a characteristic of alloys with low recrystallization temperatures. Strain-free grains start developing on recrystallization, giving rise to a smooth surface, thereby flattening the rough projections and undulations that existed at lower temperatures. The smoothing effect is evidence for the fact that the emittance decreases with an increase in temperature. From Fig. 1, it can be seen that the average value of normal spectral emittance is low and stable for the tungsten, 25 at.% rhenium, 1 Mol. % thoria.

Figure 2 depicts the variation of the normal spectral emittance of thoriated tungsten with the addition of rhenium at different operating temperatures. The behavior at each temperature was similar in that the emittance decreased fairly rapidly with small additions of rhenium, reached a minimum in the range of 3 at.% rhenium and 25 at.% rhenium, and then increased with increasing rhenium content. A similar behavior has been observed by other investigators for material properties such as bend transition temperature, tensile strength, and the microhardness of tungsten. In each of these cases, the decrease in the corresponding property has been attributed to the increase in the ductility of tungsten by the addition of rhenium. It is quite possible that the emittance is also dependent on the ductility of the concerned alloy, though this can only be confirmed after a series of extensive tests where the ductility is varied as an individual parameter. The tungsten, 30 at.% rhenium, 1 Mol. % thoria alloy indicated that the presence of a hard second-phase material tends to make it behave in a fashion similar to that of the brittle tungsten, which has a relatively higher value of normal spectral emittance. From an application point of view, a low and stable value of normal spectral emittance is desirable for thermionic energy converters, where it is necessary to reduce heat losses to enhance thermionic emission efficiency.

Conclusions

The photon-counting pyrometer has proved to be a useful device for measuring temperatures and evaluating the spectral emittance of refractory alloys at elevated temperatures. The normal spectral (0.535-μm) emittance data for the sintered, thoriated tungsten, rhenium alloys revealed that emittance is not a strong function of temperature or alloying content, as it is of wavelength, demonstrated by earlier investigators. In most laboratory pyrometers and advanced devices using photomultiplier tubes, the accuracy of measurement depends on the availability of the characteristics of a lamp within the pyrometer, whereas in this method the limitation can be removed by measuring the radiation flux directly using a photomultiplier tube operating in the digital mode. The digital mode of operation makes it stable and the calibration is simple. From a material study viewpoint, this technique may be used to observe changes in vacuum as the temperature is elevated.

Branstetter and Schall,[6] during their studies on the emittance of small cavities, found that cylindrical holes with a length to diameter ratio of 10:1 served as approximate isothermal enclosures. However, temperature gradients in the sample at elevated temperatures always posed a problem. The purpose of polishing a small flat surface around the hohlraum in the present case was to minimize the temperature deviations, especially since the cylindrical shape of the sample presented a symmetry about the center. A heat transfer analytical model to measure temperature distribution would certainly reveal the magnitude of the temperature gradients and also help in estimating the attendant error to the measured spectral emittance.

From the experimental data, it was observed that the reproducibility of any reading was better than ± 0.6°C. and the long-term drift in calibration has been found to be less than 2°C if the dead-time is determined periodically. The ab-

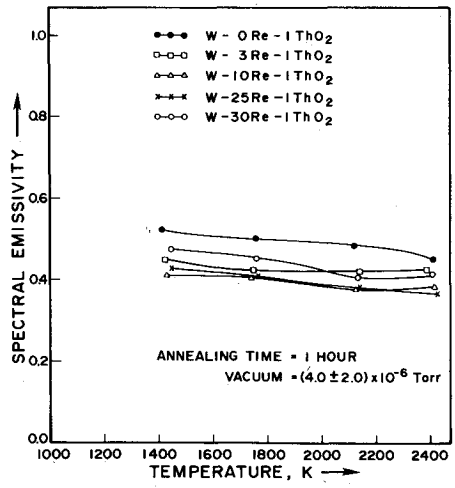

Fig. 1 Elevated temperature spectral (0.535-μm) emittance of thoriated tungsten, rhenium alloys.

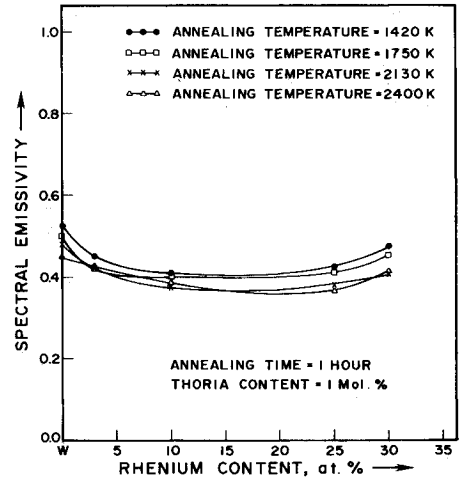

Fig. 2 Normal spectral (0.535-μm) emittance vs rhenium content for various annealing temperatures.

solute accuracy relative to the International Temperature Scale is better than 3°C, which includes an uncertainty of 1°C due to the variation of temperature with focal distance. The accuracy on the emittance measurement has been found to be better than 0.02. The accuracy of the device deteriorates above 2500 K. It has been found that the use of an interference filter rather than a glass absorber helps in increasing the overall accuracy of the device.

Acknowledgment

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Errata

1987 *Journal of Thermophysics and Heat Transfer* Index

[JTHT 1, pp. 379-383 (1987)]

THE following entries did not appear in the 1987 annual index:

Analysis of Radiation-Induced Natural Convection in Rectangular Enclosures. B.W. Webb and R. Viskanta, *Purdue University* (1, 2, p. 146) Article

Prediction of Film Boiling Wakes Behind Cylinders in Cross Flow. Rajeev Kaul, *Pipeline Hydraulics Engineering*, and Larry C. Witte, *University of Houston* (1, 2, p. 186) Engineering Note

Simultaneous Conduction and Radiation in a Two-Layer Planar Medium

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Raleigh, North Carolina

[JTHT 1, pp. 154-161 (1987)]

THE following corrections made by the authors were not included in the published paper:

The factor 2π on the right-hand side of Eqs. (10a), (10b), (A1), and (A2) should have been $\frac{1}{2}$.

Page 155:

Equations (10a) and (10b) should begin

$$Q_1^r(\tau)=\frac{1}{2}\left\{\theta_L^4 E_3(\tau)-I_1(\tau)+\sum_{\ell=0}^{L_1} h_{1,\ell}\ell!\left[(-1)^{\ell+1}E_{\ell+3}(\tau)\right.\right. \quad (10a)$$

$$Q_2^r(\tau)=\frac{1}{2}\left\{\theta_R^4 E_3(\tau_2-\tau)+I_2(\tau)\right. \quad (10b)$$

Page 160:

Equations (A1) and (A2) should begin

$$d_{1,m}=\frac{1}{2}\left\{\theta_L^4 m!\left[\left(\frac{1}{m+2}-\sum_{j=0}^{m}\frac{\tau_1^{m-j}}{(m-j)!}E_{j+3}(\tau_1)\right)\right.\right. \quad (A1)$$

$$d_{2,m}=\frac{1}{2}\left\{\theta_L^4\Gamma_1\sum_{j=0}^{m}\frac{m!}{(m-j)!}\right. \quad (A2)$$

Melting of a Horizontal Substrate Placed Under a Heavier and Miscible Pool

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[JTHT 1, pp. 321-326 (1987)]

SEVERAL errors were inadvertently introduced during production of the paper:

Page 321:

In the Nomenclature, the correct definition for β is

β = power in the relation $q'' \propto (R-1)^{\beta}$

Page 324:

Replace p in Eqs. (20-22) with ρ. The corrected equations should read

$$\omega=\left[\frac{2g(R-1)k^4\Delta T^4}{\nu r_0^2\rho^4 h_{sf}{}^4}\right]^{1/5} \quad (20)$$

$$q''=\rho h_{sf}\omega=\left[\frac{2g(R-1)k^4\Delta T^4\rho h_{sf}}{\nu r_0^2}\right]^{1/5} \quad (21)$$

$$q''=\left[\frac{g(R-1)k^4\Delta T^4\rho h_{sf}}{8\pi\nu[(R+1)/(R-1)]^{2/3}(\nu^2/g)^{2/3}}\right]^{1/5} \quad (22)$$