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A Database of Normal Spectral Emissivities of Metals at High Temperatures[1]

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The normal spectral emissivity and its time variation were measured systematically for a total of thirty kinds of pure metals and alloys at temperatures between 780 and 1200°C. The spectral data were obtained at about 100 wavelengths from 0.55 to 5.3 μm under different environmental conditions including oxidation. The spectral data were stored in a database with supplementary information on the specimens. Clear oscillations of the spectral emissivity with time and wavelength were observed for nickel, Inconel, and SUS444 as surface oxidation progressed, while emissivity variations were rather monotonic for other metals such as titanium, cold-rolled steel, and SUS310S. The surface roughness was measured for all specimens by a contact-type instrument before the measurements, and recorded as supplementary information in the database. The database was built on a personal computer operating system (Windows95) to facilitate the dissemination to researchers and engineers interested in the emissivity of metals. Indexes to the emissivity data are metal name, wavelength, temperature, time, and degree of oxidation represented by an effective thickness of oxide film on the specimen surface.

KEY WORDS: high temperature; metal; spectral emissivity; oxidation.

1. INTRODUCTION

The spectral emissivity of a clean metal surface is small and stable, but it changes drastically when the surface is oxidized. Since the spectral emissivity of metals under oxidation is very important to radiation thermometry, many measurements have been made. There was a comprehensive compilation of spectral emissivity measurements for a variety of metals

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27 years ago [1]. It was the only major compilation of spectral emissivity that attempted to include supplementary information on the specimens. The compilation is still very useful, but,the data are insufficient to apply to industrial radiation thermometry. Thus, the use of those data is limited to reference information on emissivities because most of the emissivity measurements were made under unidentified or incomplete conditions, e.g., detailed information on surface roughness and degree of surface oxidation was often lacking, and the measurement wavelengths and temperatures were relatively few.

We have developed an emissivity measurement system for metals [2] and systematically obtained a large amount of normal spectral emissivity data at nearly continuous wavelengths and temperatures with specified surface roughness to build an emissivity database for metals. The data are described in a standardized format, and the database contains both the emissivities and supplementary information of the specimens.

2. MEASUREMENT

The measurement system and the specimen shape are described in another paper in this issue [2]. The specimen was heated by direct current in a vacuum or oxidizing environment. The normal spectral emissivity was obtained at about 100 wavelengths from 0.55 to 5.3 μm and at temperatures from 780 to 1200°C.

The average and maximum values of surface roughness were measured for each specimen at the middle of the front surface in the horizontal and vertical directions before the emissivity measurement. The surface roughness meter has a contact-type probe and a high-pass filter with a cutoff length of 0.8 mm.

Several specimens were prepared for each kind of metal, and time variations of the normal spectral emissivity were measured for respective specimens according to three different measurement procedures. The first measurement procedure was such that a specimen was heated from room temperature to a high temperature in a vacuum, and the temperature was varied between 780 and 1200°C at a rate of 2 or 3°C $\cdot$ s^{-1}. The chamber was continuously evacuated by a turbo-molecular pump.

The second measurement procedure was such that a specimen was, at first, heated to a certain temperature near 1000°C in a vacuum, and then the evacuation valve was closed, and air or an oxygen–argon mixture was introduced into the vacuum chamber at a constant flow rate.

The third procedure was such that a specimen was at first heated to about 600 or 1000°C in the atmosphere of the room to heavily oxidize the specimen surface before the emissivity measurement. Then the normal spectral emissivity of the specimen was measured at high temperatures in a vacuum according to the first measurement procedure. Some specimens oxidized according to the second measurement procedure were also used in the third measurement procedure.

An additional measurement procedure was used for some stainless-steel specimens that were heated in the atmosphere of the room with the time variation of temperature simulating an actual industrial annealing process for stainless steel.

3. DATABASE SYSTEM

3.1. Database Operation

The normal spectral emissivity database was initially built on a DOS platform for Japanese computers and was subsequently modified using Access for Windows95. Figure 1 shows a data-selection form of the database. It is displayed after selecting a specific kind of metal on the opening form. Figure 1 is an example for nickel. All available measurements for the selected kind of metal are included in the data-selection form. When a line on the measurement list is selected on the data-selection form, detailed supplementary information on the measurement is displayed; the black line shows the selected measurement.

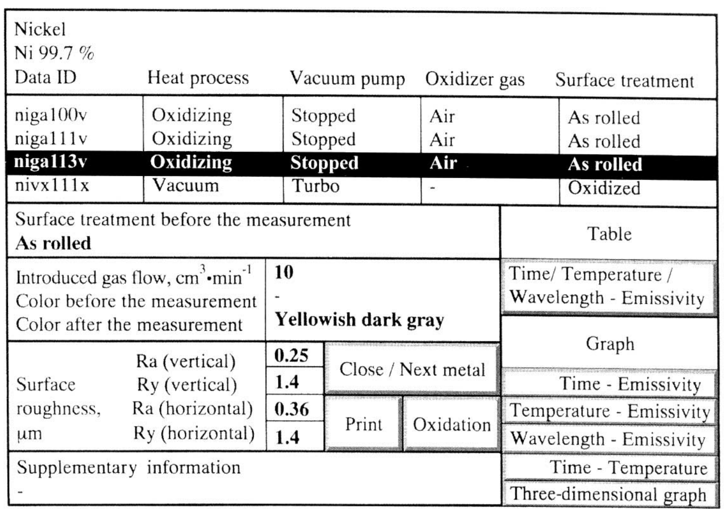

Fig. 1. Data selection form of the database.

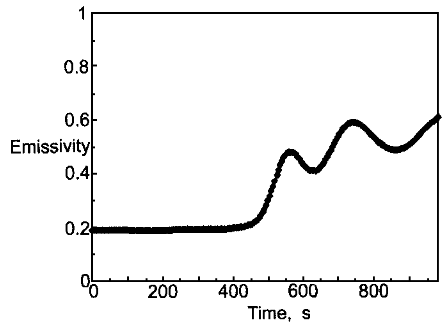

Fig. 2. A displayed graph from the database showing a time variation in the normal spectral emissivity of a nickel specimen at a wavelength of 2 μm. The specimen was heated at 1100°C in a vacuum, and then air was introduced into the vacuum chamber at a flow rate of 10 $cm^3 \cdot min^{-1}$. The average surface roughness of the specimen in the vertical direction was 0.25 μm.

Normal spectral emissivity data for the selected measurement can be displayed as a table and graphs according to selections by indexes such as wavelength, time, and temperature. Figure 2 shows an example of a displayed graph when the graph button (emissivity-time) and a wavelength of 2.002 μm are selected. A wavelength selection form is displayed when the graph button is selected. Three-dimensional graphs of time variations of normal spectral emissivities are also displayed. (They are shown in Figs. 6 to 9.)

In the cases where measurement data have clear oscillations of emissivity against time, as shown in Fig. 2, the degree of oxidation can be represented by a rough estimation of an effective thickness of the oxide film on the specimen surface. Figure 3 shows an example of such a case. The effective thickness including the refractive index of the oxide film was calculated on the assumption that the emissivity oscillations were produced by interference of radiation emitted by the interface between the oxide film and a vacuum with radiation originally emitted by the interface that was successively reflected by the metal surface. The difference between the effective thickness of the oxide film at a peak of an emissivity oscillation at a given wavelength and that at the nearest valley of the emissivity oscillation is a quarter of the wavelength. The time variation of the effective thickness shown in Fig. 3 is the average obtained at several wavelengths. The agreement of effective thicknesses calculated at different wavelengths was not very good; the difference was as large as 10% in this case.

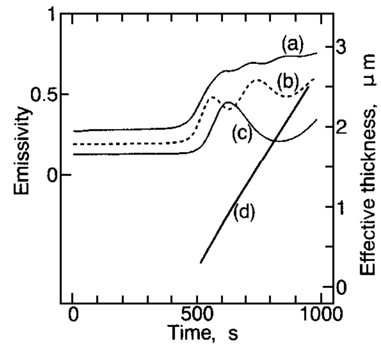

Fig. 3. Time variations in the normal spectral emissivity of a nickel specimen and in the effective thickness of the oxide film on the specimen surface. This is from the same data source as Fig. 2 (a) for the emissivity at a wavelength of 1.1 μm, (b) for the emissivity at 2 μm, (c) for the emissivity at 3.7 μm, and (d) for the effective thickness of the oxide film.

3.2. Database Contents

The database has emissivity data from a total of 182 measurements on various metals: titanium, nickel, copper, molybdenum, and tungsten, three kinds of cold-rolled steel, four kinds of electromagnetic steel, Inconel 600, Inconel 601, Inconel 625, Kovar, Monel, Nichrome, Permalloy 45, Permalloy 78, three kinds of JIS SUS304 (ANSI304, DIN1.4301), JIS SUS310S (ANSI310S), JIS SUS316, JIS SUS329J2L (NAR DP-3, YUSDX-1, R22CR), JIS SUS430 (ANSI430, DIN1.4016), JIS SUS444 (NSS444N, NAR192, YUS190), Ni36 (Invar, Umber), and painted cold-rolled steel.

Since the normal spectral emissivity data obtained in this research are too many to show, only selected emissivity data will be presented as examples in this paper. Figure 4 shows normal spectral emissivities of an as-rolled specimen (a), a polished specimen (b), and abraded specimens (c)–(e) of electromagnetic steel. The specimens were heated to 1100°C according to the first measurement procedure. The average surface roughness values of specimens (a)–(e) in the vertical directions were 0.22, 0.05, 0.05, 0.11, and 0.38 μm, respectively. The emissivity of the polished specimen was the lowest, and the emissivities of the abraded specimens had a small variation according to the surface roughness.

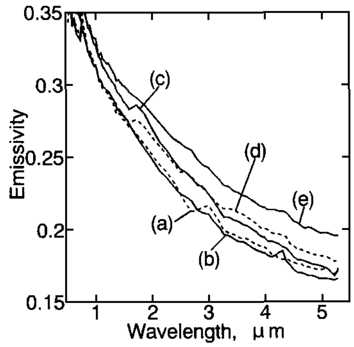

Fig. 4. Normal spectral emissivities of electromagnetic steel (JIS 50A1000) specimens heated at 1100°C in a vacuum. (a) As-rolled specimen, (b) polished specimen, (c) specimen abraded by paper of JIS No. 1500, (d) specimen abraded by JIS No. 800, and (e) specimen abraded by JIS No. 150.

Figure 5 shows time variations in the normal spectral emissivities of four specimens of Inconel 601 at a wavelength of 2 μm. The specimen surfaces were oxidized with different oxidizing gases at 1000°C according to the second measurement procedure. The average surface roughness values of specimens (a)–(d) in the vertical directions were 0.25, 0.19, 0.14, and

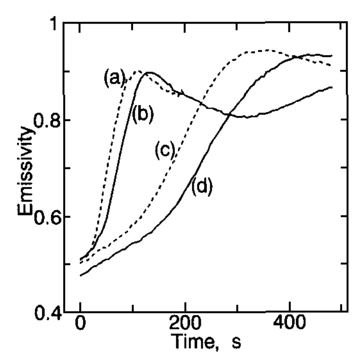

Fig. 5. Time variations in the normal spectral emissivities of four specimens of Inconel 601 at a wavelength of 2 μm. The specimens were heated at 1000°C, then oxidized with air or different mixtures of O_2 in argon introduced at a flow rate of 1 $cm^3 \cdot min^{-1}$: (a) 10% O_2; (b) air; (c) 1% O_2; (d) 100 ppm O_2.

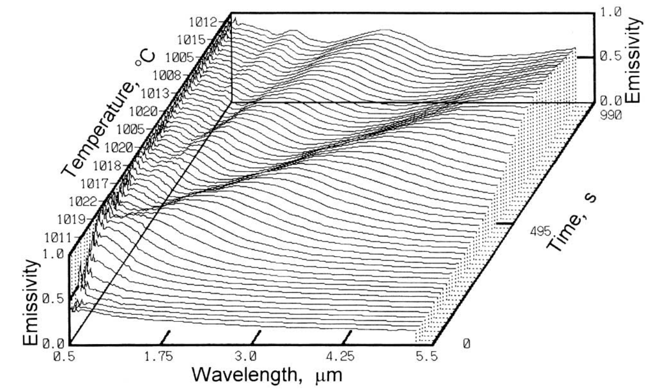

Fig. 6. Time variation in the normal spectral emissivity of a JIS SUS444 specimen when air was introduced into the vacuum chamber at a flow rate of $0.2\,cm^3 \cdot min^{-1}$.

0.11 μm, respectively. After the measurements, the metallic color of the specimens had changed to black from oxidation. It is seen that a higher oxygen content caused a more rapid rise of emissivity.

Figures 6–9 are three-dimensional graphs showing time variations of the normal spectral emissivities for JIS SUS444, cold-rolled steel, tungsten, and Monel, respectively. The average surface roughness values of the specimens in the vertical directions were 0.05, 1.0, 0.53, and 0.43 μm, respectively.

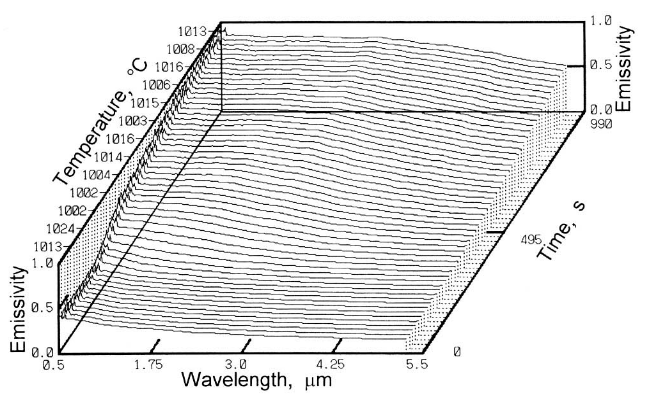

Fig. 7. Time variation in the normal spectral emissivity of a cold-rolled steel specimen when air was introduced into the vacuum chamber at a flow rate of $0.2\,cm^3 \cdot min^{-1}$.

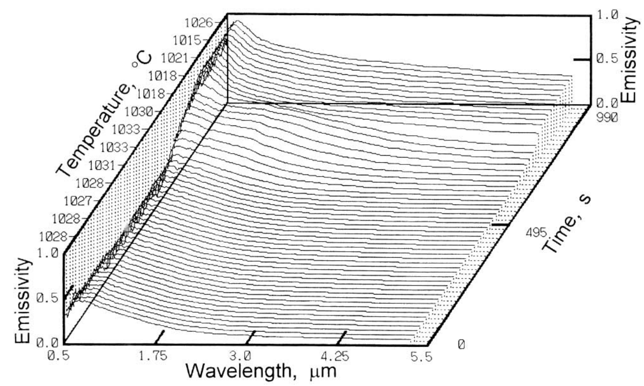

Fig. 8. Time variation in the normal spectral emissivity of a tungsten specimen when air was introduced into the vacuum chamber at a flow rate of $1\ cm^3 \cdot min^{-1}$ (from 0 to 500 s) and then $10\ cm^3 \cdot min^{-1}$ (from 500 to 1000 s).

Figure 6 shows a time variation in the normal spectral emissivity of a JIS SUS444 specimen when it was heated in a vacuum at 1000°C and then oxidizing gas was introduced according to the second measurement procedure. Clear oscillations of the emissivity spectrum with wavelength and time is seen as oxidation progresses. It can be concluded that an oxide film grew on the specimen surface and that it caused interference of emitted

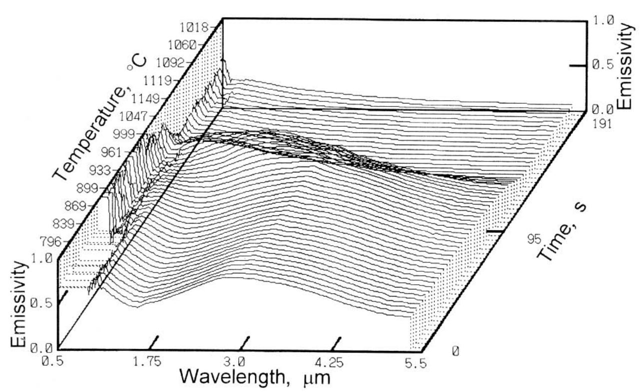

Fig. 9. Time variation in the normal spectral emissivity of a Monel specimen oxidized by heating up to about 1000°C in the atmosphere of the room before the emissivity measurement when the specimen was heated at high temperatures in a vacuum.

radiation in the oxide film. The specimen looked dark green after the emissivity measurement.

Figure 7 shows a time variation in the normal spectral emissivity of a cold-rolled steel specimen when it was heated in a vacuum at 1000°C and then oxidizing gas was introduced according to the second measurement procedure. It is seen that the emissivity increases monotonically as oxidation progresses and that the emissiviy spectrum finally became relatively flat. It is considered that the oxide film grown on the surface was opaque or diffusive, which prevented emitted radiation to interfere in the oxide film. The specimen looked dark gray after the emissivity measurement.

Figure 8 shows a time variation in the normal spectral emissivity of a tungsten specimen when it was heated in a vacuum at 1000°C and then oxidizing gas was introduced according to the second measurement procedure. The specimen shape was just a plane ribbon without folding because the tungsten was so fragile. The normal spectral emissivity of the tungsten specimen was derived by taking the normal spectral emissivity of the rear surface of the specimen coated with the heat-resisting black paint as 0.85 at the wavelength of 0.9 μm. The value of 0.85 was obtained for the heat-resisting black paint from emissivity measurements of cold-rolled steel whose front surface was coated with the same paint. It is shown in Fig. 8 that a peak in the spectral emissivity occurs at a wavelength between 0.65 and 0.7 μm as oxidation progresses. The specimen looked vivid purple after the emissivity measurement, probably due to the characteristic spectral emissivity.

Figure 9 shows a time variation in the normal spectral emissivity of a Monel specimen when the specimen was preheated in the atmosphere of the room and then heated in a vacuum above 1100°C according to the third measurement procedure. It is seen that the emissivity spectrum shows oscillations due to interference of emitted radiation in the oxide film formed on the metal surface in advance of the measurement, and that the oscillations begin to disappear at about 1000°C, and then the emissivity spectrum becomes monotonic at a low level, which is typical of clean metal surfaces. It can be concluded that the oxide film that formed in advance on the specimen surface disappeared during heating in a vacuum.

4. CONCLUSIONS

All of the normal spectral emissivities and the supplementary information on the specimens obtained in this work were stored in the described database. The database and the original text files of the emissivity data are supplied on a single CD-ROM with simple application software, and the database can be handled with the application software, Access for

Windows95, or ODBC driver. It is expected that the normal spectral emissivity database will be used for development of multiband emissivity compensation techniques in radiation thermometry and for modeling of thermal radiative properties of oxide films formed on metal surfaces.

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