High emissivity coatings for high temperature application: Progress and prospect

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1. Introduction

High emissivity coatings are widely used in many high temperature applications to effectively transfer the heat by radiation [1–4]. For example, the surface of Ni-, Fe-, Co-based alloys applied in metal thermal protection systems (MTPS) [5,6] in third generation of reused space vehicles involves high friction heat from acute friction between space vehicle surface and atmosphere, which causes obvious increase of surface temperature up to 1000 °C during hypervelocity flight [7–9]. As a result, the lifetime and performance of MTPS will be seriously degraded. Therefore, the high emissivity coating is intentionally deposited on MTPS to decrease the surface temperature by radiation.

When a radiation falls on a body it may be partially reflected, transmitted, or absorbed, which is associated with reflection (R), absorption (A), transmission (T), and emission (ε). The principle of conservation of energy ties together these radiation characteristics as A + R + T = 1. According to Kirchhoff’s law, at equilibrium for a given wavelength $\lambda$ and temperature $T$, the emissivity of any body is equal to its absorption [10], i.e. $\varepsilon(\nu, T, \theta) = A(\nu, T, \theta)$, where $\varepsilon$ is the emissivity, $\nu$ the frequency, and the angle $\theta$ specifies the observer angle. This indicates that the emissivity of an object can be indirectly obtained by measuring its absorptivity. For a uniform and isotropic opaque surface in thermal equilibrium, the transmission is zero, the relationship between the emissivity and the reflectivity is: $\varepsilon(\nu, T, \theta) = A(\nu, T, \theta) = 1 - R(\nu, T, \theta)$. Many materials can be considered as opaque body. The emissivity here is characterized to describe the surface radiative property which involves the transfer of heat by electromagnetic radiation arising due to the temperature of a body. The emissivity is defined as the ratio of energy radiated by the material to energy radiated by a black body (A body that emits the maximum amount of heat for its absolute temperature is called a black body, meaning that a blackbody completely absorbs all radiation incident upon it, and at the same time it emits all the energy that it absorbs with the same absorbing spectrum. That is to say, $\varepsilon = 1$ at the same temperature, which is described by Eq. (1):

$$
\varepsilon(T) = \frac{\int_{\lambda}^{\infty} \varepsilon(\lambda) E_{\lambda} d\lambda}{\alpha T^4}
$$

(1)

Where $E$ is radiant heat of gray body to its surroundings, $\varepsilon$ hemispherical emissivity of the gray body (dimensionless), $\alpha$ Stefan–Boltzmann constant ($5.67 \times 10^{-8}$ W/(m²·K⁴)), $T$ temperature (K). The emittance is dependent on direction and wavelength, thus the radiance ability can also be evaluated by the spectral emissivity and directional emissivity, described as Eqs. (2) and (3) respectively:

$$
\varepsilon_{\lambda}(\lambda, T) = \frac{E_{\lambda,\text{actual emitted}}(\lambda, T)}{E_{\lambda,\text{black body}}(\lambda, T)} = \frac{E_{\lambda}(\lambda, T)}{E_{\lambda,\text{black body}}(\lambda, T)}
$$

(2)

$$
\varepsilon(\theta, \phi, T) = \frac{\int_{\lambda}^{\infty} L_{\lambda,\text{actual emitted}}(\lambda, \theta, \phi, T) d\lambda}{\int_{\lambda}^{\infty} L_{\lambda,\text{black body}}(\lambda, \theta, \phi, T) d\lambda} = \frac{L(\theta, \phi, T)}{L(0, 0, 0, T)}
$$

(3)

A real object does not radiate as much as a perfect black body, which radiates less heat than a black body and is called gray body ($\varepsilon < 1$).

Thermally emitted radiance from any surface mainly depends on two factors. (1) the surface temperature, which is an indication of the equilibrium thermodynamic state resulting from the energy balance of the fluxes between the gray body surface and its surroundings; and (2) the surface emissivity, which is the efficiency of the surface for transmitting the radiant energy generated in the surface into its surroundings. The latter depends on the temperature (but the relationship between emissivity and temperature is not definite,
depending on material nature, surface parameters and wavelength), composition, surface roughness, coating thickness, wavelength, and physical parameters of the surface. Here we review recent progress with emphasis on the discussion of the design methodology, followed by briefing the emissivity characterization. Lastly, the prospects for research and technology in high emissivity coatings will be summarized.

2. Design methodology

2.1. Doping

According to Wien’s displacement law and Planck’s law [11], most energy of the black body at high temperature is radiated in the wavelength range of 1–5 μm, however it happens that many materials have the weak intrinsic absorption within this range. As a result, the emissivity in this region is quite low since the object’s absorptivity and emissivity spectra are identical in thermal equilibrium state. Extensive work proves that total emissivity or spectral emissivity could be effectively enhanced via doping (doping refers to the process of intentionally introducing impurities into an extremely pure material). Several mechanisms for doping enhanced emissivity in the wavelength range of 1–5 μm were proposed for different materials, namely, free carrier absorption mechanism (the phenomenon whereby an electron within a band absorbs radiation by transferring from a low-energy level to an empty high-energy level) [12], d–d transitions in octahedral coordination [13,14], distortion of the crystal lattice [15]. For semiconductor material, free carrier absorption mechanism generally dominates the emissivity enhancement in the wavelength region of 1–5 μm. Fig. 1 shows the absorption coefficient as a function of wavelength for three different SiC specimens with different impurity (dopant) concentrations [16]. It is obvious that increase in impurity concentration strengthens the absorption in the wavelength range of 1–5 μm. As higher impurity concentration causes more free electrons, more electrons within a band absorb more radiation by transferring from a low-energy level to an empty high-energy level, leading to more absorption. As such, the emissivity is accordingly enhanced within this wavelength range as the impurity concentration increases since the object’s absorptivity and emissivity spectra are identical in thermal equilibrium state.

In glassy oxide coatings, different excitations are responsible for the absorption of electromagnetic radiation [17]. It is suggested that suitable dopants with transition metal oxides doped in silicate glasses may yield emissivity as high as 0.9 in the whole temperature range. For example, the d–d transitions of Cr^{3+} in octahedral coordination play an important role on the absorption [13,14]. The emissivity spectra at room temperature for 0.1%, 0.25% and 0.5% Cr_{2}O_{3} doped compounds as shown in Fig. 2 indicates that the concentration of Cr_{2}O_{3} dramatically enhanced the normal spectral emissivity between 1 and 5 μm (i.e. 2000–10,000 cm⁻¹). This enhancement is related to formation or precipitation of new phases on the grain boundary due to substitution, which will change the grain boundary area. But the mechanism still needs to be further digested.

Another consequence caused by dopant is the crystal distortion due to different ion radii, which also has the contribution to radiation. Pratt et al. incorporated NiO into MgO-Al_{2}O_{3}-SiO_{2} system glasses heated at 1020 °C for 2 h and the whole-band normal direction emissivity changes from 0.82 to 0.90 by doping NiO [18]. When the Ni^{2+} is incorporated into cordierite structure and substituted with Mg^{2+}, the order degree of Al/Si in crystal structure of cordierite is decreased due to different radii of Ni^{2+} and Mg^{2+}, leading to the crystal structure distortion. This in turn decreases the symmetry of lattice vibration, thus enhances the effects of anharmonic vibration of polar lattice, the coupled action of phonon, and phonon combination radiation. Therefore, the infrared radiance of this material is enhanced by NiO doping.

Moreover, the dopant (rare-earth oxides and transition elements) could tune the spectral emissivity thus change the emissive power [19,20]. Incorporation of 2–4 wt. % Co_{3}O_{4} or NiO into MgO host (a low infrared emissivity) produced “matched emitters”, which means its emissive power spectrum is matched very efficiently to the response of GaSb photovoltaic cells that convert the infrared radiation into electricity. Fig. 3 shows the continuous, strong radiant emissions which is up to 0.9 in the optimal energy range between 1 and 2 μm and minimal radiation at higher wavelengths [21,22]. The total emissive power between 1 and 9 μm is calculated by integrating the area under each curve. Interestingly, both the blackbody emitter and the NiO-doped MgO emitter have the same total emissive power of 144,000 W cm⁻². However, it is noticeable that the NiO-doped MgO emitter emits most of power at wavelengths less than 2 μm, instead of 1–5 μm in theoretical blackbody. The phenomenon results from intratomic electronic transitions determined by the electronic configuration of the dopant ions and interactions with the coordinating crystal field of the host oxide [23].

2.2. Surface roughness

The correlation between emissivity and surface roughness has been explored both theoretically [24,25] and experimentally [26,27]. Wen et al. [24] modeled the effect of surface roughness on emissivity of aluminum alloys. Normally the surface involves two broad categories: optically smooth (ideal) and rough (real) surfaces. For
optically smooth surfaces, spectral emissivity is determined by combining Fresnel’s equation and Kirchhoff’s law yielding

\[ \varepsilon_{\lambda} = \frac{4n^2}{(n + 1)^2 + k^2} \tag{4} \]

Where \( n \) is the index of refraction and \( k \) the extinction coefficient. Fig. 4(a) compares spectral emissivity values using three different methods. It indicates that the experimental result shows the same trend as calculated one. Namely, the emissivity decreases as wavelength increases in the infrared range for most metallic surfaces.

For real surfaces, the surfaces can be divided into three regions based on optical roughness \( \sigma/\lambda \), the ratio between surface roughness to wavelength: the specular region \((0 < \sigma/\lambda < 0.2)\), intermediate region \((0.2 < \sigma/\lambda < 1)\) and the geometric region \((\sigma/\lambda > 1)\). In the specular region, it assumes that the reflection of incident radiation is specular, and the diffraction theory is used to predict the effects of surface roughness on emissivity [28,29]. For a Gaussian distribution of surface heights, the relationship between reflectance and optical roughness follows an exponential decay function of \( \sigma/\lambda \), which is identified both theoretically [30,31] and experimentally [32,33],

\[ \rho_r = \rho_p \exp \left[ -\frac{4n^2\sigma}{\lambda^2} \right] \tag{5} \]

where \( \rho_r \) and \( \rho_p \) are the reflectances for a rough surface and a polished surface, respectively. Eq. (5) reveals that the larger \( \alpha \) could result in lower reflectance, i.e., higher emittance, which is verified in aluminum-coated ground glass as shown in Fig. 4(b) [29]. In the intermediate region, the directional reflectance \( \rho_\downarrow(\theta_i) \) can be determined by integrating the bidirectional reflectance function, \( \rho_\downarrow^b(\theta_i, \theta_t) \) over the respective hemisphere for a given angle of incidence [34] as indicated in Fig. 4(c). According to Kirchhoff’s law and energy conservation, the directional emissivity can be calculated by Eq. (6)

\[ \varepsilon_\downarrow(\theta_i) = 1 - \rho_\downarrow^b(\theta_i) \tag{6} \]

Buckius et al. [35–39] theoretically confirmed that increased roughness increases directional emissivity in the intermediate region. In the geometric region, geometric optics is used to predict emissivity, ignoring the diffraction effects. Surfaces with repeatable grooved finish, like V-shaped grooves [40], circular grooves [41], and pyramidal grooves [42], are commonly used to model the emissivity enhancement. The slope of the grooved surface plays an important role in emissivity enhancement. For example, the inter-reflection caused by a 60° V-groove in Fig. 4(c) and a small grove angle (also the slope) in Fig. 4(d) could significantly enhance the normal emissivity. Overall, modeling results lead to a conclusion that the emissivity is dependent on surface roughness for \( \sigma/\lambda < 1 \) and on surface slope for \( \sigma/\lambda > 1 \).

In experiment, the emissivity enhancement due to roughness was verified in opaque materials, such as steel [26] and Pr2NiO4 coatings [27]. Fig. 5 compares normal spectral emissivity of rough Pr2NiO4 coating and single crystal Pr2NiO4 (considered as smooth surface) in the \((a-b)\) plane at 1000 K, in the working temperature range of the infrared radiator, from far to midinfrared. The spectral response of the coating is 30% to 40% higher than that of the single crystal, which is largely dominated by the infrared absorptions produced by localized polaron. Clearly, the enhancement of the intrinsic absorption is obtained by increasing the optical path of the light between each small cavity of the surface. Furthermore, the effect produced by the rough Pr2NiO4 coating is also clearly demonstrated in Fig. 5. The low normal spectral emissivity of the original semitransparent ceramic in the midinfrared range (from 2500 to 5000 cm\(^{-1}\)) is completely occulted after the deposit.

Although the previous achievements provide valuable insight into the emissivity principles concerning the relationship between emissivity and surface roughness, the influences of surface roughness on emissivity remain illusive, and sometimes current emissivity models are consistent with experimental emissivity values. A universal emissivity model concerning roughness effect needs to be proposed in order to completely agree with the practically measured emissivity.

2.3. Surface texture

The spectral radiative properties were completely dependent on the competition between the absorption coefficient (following the wavelength) and the radiative scattering. The surface texture (in materials science, texture is the distribution of crystallographic
orientations of a sample) often forming during coating deposition, has an important effect on radiative scattering. For example, a surface texture with high aspect ratio feature (height to width ratio \(N \approx 5:1\)) can serve as a collection of a lot of individual black-bodies, which exhibit an emissivity of around 0.85 \([43]\). The theoretical and experimental results of IR spectral emittance of nonsphere-shaped particles indicate that coating composing of oriented rhenium whiskers with high aspect ratio (Height/Dimension = 5) provides the high emittance value, compared to that of randomly oriented whisker coating \([44,45]\). However, the texture effect on emissivity is still in argument. Recently, Rozenbaum et al. \([46]\) found that unlike the other previously studied ceramics, the highly textured alumina ceramic has a much lower emissivity than the single crystal between 1300 \(\text{cm}^{-1}\) and 1800 \(\text{cm}^{-1}\) (shown in Fig. 6) and the spectral emissivity of this sample was radically different from the emissivity spectra of lowly textured alumina. In this range, due to the weak absorption coefficient, the radiation mean path inside the sample was higher than the thickness of the single crystal. For longer wavelengths, the emissivity increases to become higher than those of the single crystal and tends to those of the lowly textured sample in the transparent zone. This is in good agreement with the previous reports. So it is concluded that we should consider wavelength range when we discuss the texture effect.

Fig. 5. Normal spectral emissivity at \(T = 1000\) K and from 400 to 5000 \(\text{cm}^{-1}\) of cordierite–mullite substrate (dashed line), single crystal of Pr\(_2\)NiO\(_4+\delta\) (dotted line), and rough Pr\(_2\)NiO\(_4+\delta\) coating on the cordierite–mullite substrate (solid line) \([27]\).

Fig. 6. Normal spectral emissivity of alumina ceramics (thickness = 1 mm, \(T = 1\), 350 K) with two different textures \([46]\).
polarizations [47]. Beyond the photonic band gap regime, there are two strong absorptions: one is located at $\lambda = 2.5 \, \mu m$ with an absorptance of $\sim 40\%$ and the other located at $\lambda = 1.5 - 1.9 \, \mu m$ with an even stronger absorptance of $\sim 80\%$. As discussed above, Kirchhoff’s law tells us that at equilibrium for a given wavelength $\lambda$ and temperature $T$, the emittance of any body is equal to its absorptance [10]. Thus, a strong narrow absorption is suggestive of a narrow band emission from a photonic-crystal sample.

In experiment, the measured power-density spectrum of the sample in Fig. 8 is compared with that computed for a blackbody cavity radiator at $T = 750$ K. The blackbody radiation follows the Planck radiation. In the bandgap, the emission is suppressed below the blackbody emission. However, photonic-crystal emission in the peak regime is found to exceed that of the blackbody by $\sim 300\%$. Note the photonic band gap emission exhibits a narrow FWHM of $\Delta \lambda \sim 1.8 \, \mu m$ while black body shows a wide FWHM of $\Delta \lambda \sim 4.5 \, \mu m$. The absorption rate of 3D metallic photonic crystal is found to be suppressed in the photonic band gap regime ($\lambda \sim 8 - 16 \, \mu m$) and strongly enhanced at the photonic band edge ($\lambda \sim 6 \, \mu m$). The peak absorption in tungsten photonic crystal is an effective absorption that originates from the intrinsic tungsten absorption and is subsequently enhanced by the photonic band edge effect. The enhancement is attributed to a longer photon–matter interaction length as compared to the metallic skin depth, the slower group velocity of light at the band edge, and the finite metallic absorption constant. It should be stressed that the photonic-crystal by no means exceeds the blackbody emission in the entire wavelength spectrum, rather the exceeding happens at the neighborhood of the band-edge only [55]. Although the photonic crystal has been rapidly developed, the coating or thin film of photonic crystal has not been realized yet.

### 2.5. Coating thickness

As mentioned above, when a radiation falls on a body, it may be partially reflected, transmitted, or absorbed. As such, light penetration depth (defined as the inverse of the absorption coefficient ($\alpha$)) is closely related to the emissivity of coatings. For the light with the wavelength $\lambda$, the depth of light penetration, $d_p$ is associated with the extinction coefficient ($k$), given by

$$d_p = \frac{1}{\alpha} = \frac{\lambda}{4\pi k} \quad (7)$$

Eq. (7) indicates that $d_p$ is inversely proportional to $k$. Thus, $k$ is expected to be as low as possible in order to get high emissivity of coatings. As a result, the coating is expected to be as thick as possible, at least thicker than $d_p$ (otherwise, the transmittance will occur). But in practice it is impossible to fabricate unlimitedly thick coating due to production cost or fabrication limitation. In the past, models and

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**Fig. 7.** (a) A SEM view of a 3D tungsten photonic crystal. Within each layer, the 1D rod width is 0.5 $\mu m$ and the rod-to-rod spacing is 1.5 $\mu m$. (b) A computed absorption spectra for an eight-layer 3D tungsten photonic-crystal sample. [51].

**Fig. 8.** Comparison of emission power density between the photonic-crystal sample and a blackbody cavity radiator at $T = 750$ K [52].
experiments concerning the relationship between emissivity and coating thickness were explored in details [56]. A typical relationship between them in particle embedded in $\text{Al}_2\text{O}_3$ coating is shown in Fig. 9, revealing that initially the emissivity increases rapidly as thickness increases and becomes steady above thickness of 40 μm. Similar relationship was also found in other ceramic coatings, such as SiC, $\text{Si}_3\text{N}_4$ and $\text{Al}_2\text{O}_3$ [5], anodic film on aluminum [57], $\text{Si}_3\text{N}_4$ and $\text{SiO}_2$ on silicon substrates [58]. Therefore, it is concluded that the coating has a critical thickness over and above which emissivity almost does not change.

When the coating has more than two layers (called multilayer coating), the optical interference will happen. If the thickness of multilayered coatings falls into the same order of magnitude as the incident radiation, a considerable amount of optical interference within the multilayer structure tends to occur [59]. The net surface reflectivity and absorption often change significantly even though there is any thickness change in any layer. The resultant temperature profiles and quality of the film are therefore affected by these changes in optical properties. This was evident in $\text{SiO}_2$/Si system, as shown in Fig. 10 [60]. The relationship between emissivity and thickness shows a converted “V” shape. The emissivity peaks at the $\text{SiO}_2$ thickness of around 240 nm for a given wavelength. When the coating is ultra thin, approaching zero, smaller than the wavelength of the radiation light, the increase of emissivity is ascribed to the coating thickness. The reflections from the second interface are in phase with the one from the first interface, resulting in a high reflection and low emissivity. As the coating thickness increases, when the phase difference of reflected lights from surface and interface is equal to the radiation light wavelength, extinction happens where the emissivity reaches the maximum value. As the thickness further increases, this phase difference deviates from the wavelength and causes the emissivity decreasing. However, this critical thickness (from several tens to 100 μm) where interference of radiation light occurs depends on the coating composition [61].

2.6. Nanocomposite coatings

For normal incident radiation, reflection coefficient $R$ is given by the Fresnel’s formula:

$$R = \frac{(n - 1)^2 + k^2}{(n + 1)^2 + k^2}$$

(8)

where $n$ is the refractive index, $k$ the extinction coefficient. According to Eq. (4), the extinction coefficient $k$ becomes much larger than 1 when spectral emissivity $\varepsilon$ is approaching the maximum value of 1. Eq. (8) states the reflection coefficient tends to reach a maximum value of 1. As a result, there is an abrupt decrease of $\varepsilon$ while $R$ has a sudden increase as wavelength increases, which is clearly demonstrated in Fig. 11 for boron nitride [62]. Note that a peak of $R$ in Fig. 11 (a) accompanies with a sudden drop of emissivity and Fig. 11 (b). This concluded that single component material can hardly show high emissivity on the whole frequency range.

Besides pursuit of high emissivity, the other properties such as mechanical properties, thermal shock resistance and oxidation resistance, should be also taken into account when high emissivity coatings are used at high temperature (≥1000 °C) like MTPS. However, single component coating could rarely possess these comprehensive properties. Designing nanocomposite coatings may help a lot. A nanocomposite coating comprises of at least two phases: a crystalline phase and an amorphous phase, or two different crystalline phases, in which at least one is capable of absorbing and re-radiating thermal energy (emissivity agents), such as BN, SiC, $\text{SiB}_6$, traditional metal oxides, refractory metals carbides [63]. The other phase is like binder such as colloidal silicon dioxide, which can provide high strength, thermal expansion characteristics similar to their intended substrates, and adequate bond strength with the substrate [64]. These composite coatings represent a new class of materials, whose mechanical or emittance properties are not subjected to volume mixture rules, but depends on synergetic interactions of the composite constituents.

Recently, our group deposited SiC/$\text{SiO}_2$ composite coating on the pre-oxidized 316 SS substrate via EB-PVD technology [65,66]. It is interesting to find that nanocrystalline SiC deposited at high temperature was formed, as shown in Fig. 12, giving rise to the nanohardness as high as 50 GPa. At the same time, it is well known that SiC exhibits very good emittance property. Combination of emittance and mechanical properties makes SiC promising applied in high temperature environment or space, like MTPS [67]. In SiC/$\text{SiO}_2$ system, SiO$_2$ can act as an additive oxidation insulator because of low thermal conductivity and high oxidation resistance. The spectral directional emissivity of SiC/$\text{SiO}_2$ composite thin film almost keeps a constant of around 0.65 at a wide wave-number range from 400 to 4000 cm$^{-1}$, as shown in Fig. 13. Unfortunately, the other properties like oxidation resistance, shock resistance, have not been investigated. But it can be predicted that the nanocomposite coatings are a promising branch of materials that could potentially possess both high emissivity and unique mechanical or thermal shock resistance properties.

Another composite coating structure, i.e. multilayer, is proposed in order to meet comprehensive requirements, such as oxidation, emittance, and low catalysis characteristics in hypersonic structures. In the multilayered system, normally five different layers are realized (schematically shown in Fig. 14) [68]: (i) low catalysis layer (based on borosilicate or borophosphate glasses) to minimize aerothermodynamic heating; (ii) the high-emittance layer consisting of various
Fig. 11. Reflectance and emittance of boron nitride [62].
constituents, such as SiB₆, providing emittance enhancement to the total system; (iii and iv) the oxygen-resistance layer to block oxygen diffusion, comprising of a base layer and sealing layer; (v) reaction barrier layer (like Al₂O₃, TiAl₃) to prevent reaction between the substrate alloy and the other coating layers. It is recognized that thermal expansion coefficient differences between layers are inherent in this multilayer design. Accordingly, we can accommodate thermal strains by adjusting the layer thickness, and its self-healing characteristics can help avoid the cracking that may occur.

Bird et al. realized this multilayer design by sol–gel method [68]. The emittance layer of the coating imparted an emittance in excess of 0.8 during exposure at 980 °C for up to 100 h, which was at least 15% greater than that for the coated alloy without the emittance layer as shown in Fig. 15. Likewise, the low catalysis outer layer of the coating reduced the catalytic efficiency for recombination of atomic oxygen and nitrogen in hypersonic flowing air. The catalytic efficiency of coated Inconel 617 was reduced by a factor of four, compared to the uncoated condition, for a 1-h exposure at 980 °C.

To summarize, nanocomposite coatings with multiple components or multilayered structure may be most attractive to reach high emissivity value within the whole frequency range as well as excellent mechanical or thermal properties. The research of multilayer design has just begun, and it is expected to attract ever increasing attention in the near future.

3. Emissivity characterization

In a classical definition, emissivity measures the ability of a material to radiate the heat through electromagnetic wavelength. Emissivity measurements are difficult or tedious in practice because it is a function of several variables and an extrinsic parameter of a material. Although many methods have been proposed and developed so far, a standard procedure or a universally accepted methodology does not exist yet. Qualitatively, the emissivity can be estimated by four developed basic methods: Calorimetric method [69–71]; optical reflectivity method [72], multispectral radiation thermometry [73] and radiation energy method [74]. Calorimetric method involves measuring the heat power delivered to the test sample as well as the temperatures of the emitting surface (the sample) and the surroundings in a vacuum over time [70,71]. An energy balance is then used to

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**Fig. 12.** HRTEM and cross-sectional images of SiC thin film prepared by EB-PVD at 900 °C.

**Fig. 13.** The emissivity and reflectivity of SiC/SiO₂ composite thin film as a function of wavenumber [9].

**Fig. 14.** Schematic diagram of the multilayer coating [68].

**Fig. 15.** Emissance (a) and weight-change (b) as a function of exposure in air at 1000 °C for coated Inconel 617 with emittance coating embedded within the oxidation coating [68].
determine the emissivity. The sample must be well insulated on the side and back, and parasitic heat losses must be accounted for to accurately determine the heat transfer through the sample surface [75]. Reflectivity method involves illuminating a sample with infrared energy and measuring the percentage of energy reflected from the surface [47,46]. The absorbance is calculated from the reflectance and used to calculate normal emittance by Kirchhoff’s law and the Stefan–Boltzmann equation. Multispectral radiation thermometry (MRT) [73] employs radiation measurements at three or more wavelengths and an emissivity model [77,78]. This method could measure the spectral emissivity and temperature simultaneously based on the relationship between temperature and spectral emissivity as follows:

$$\varepsilon = \exp \left[ \beta_0 \sqrt{A} \right]$$

(9)

This method provides many advantages, such as sample-preparation fast test free, on site test, no limitation for temperature, but its accuracy is lower and there is no common model to be applicable of all the materials. The most widely method used in the assessment of emissivity of coating is energy method which is based on the measurement of radiation power of sample surface over the radiation power of black body at the same temperature (Stefan–Boltzmann equation). The key problem is to select the suitable black body which determines the measurement accuracy. More details for emissivity measurement via energy method could be found in references [74,79–83]. Fourier spectroscopy based energy method for emissivity test has been rapidly developed recently, which prides more accuracy (less than 3%) of emissivity measurement. The temperature range of measurement is from −20 to 2000 °C and the wavelength range from visible light to above 25 μm.

4. Prospect

Absorption coefficient $\alpha$ and scattering coefficient $S$ are important factors to be considered when designing a high emissivity coating; increasing $\alpha$ and decreasing $S$ can enhance the emissivity. In principle, all emissivity enhancement mechanisms can be applied to the enhancement of ceramic coatings, the real challenge lies in the implementation. However, for real engineering applications, pure and solid coatings may be more suitable for the academic driven by the industrial needs. In-situ synthesis of nanocrystalline or nanocomposite coatings (such as nc-SiC-\(\alpha\)/SiO2 or nc-SiC-\(\alpha\)/C) or designing multilayered structural layers may hold the key (at least, two of the keys) to this multifunctional coating. Another promising branch called variable emittance coating has been born with the birth of an emissivity measurement apparatus for coatings, a stand-alone machine. To catalyze the birth of the universal emissivity measurement, regular international seminars should be organized especially on this topic. Fourier spectroscopy based energy method may become the promising technique and needs further development.

References


