EMISSIVITY OF BLACK COATINGS FROM AMBIENT TO CRYOGENIC TEMPERATURES: HOW SPECTRALLY FLAT BLACK COATINGS CAN ENHANCE PERFORMANCE OF SPACE SYSTEMS

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ABSTRACT

Total hemispherical emissivity (ε) of Acktar Fractal Black™ was measured using a calorimetric method. Aluminum substrates were coated with varying thicknesses of the deep black surface coating: 20, 35 and 45 µm respectively to investigate the effect of coating thickness on the emissivity performance especially at cryogenic temperatures. The emissivity of an additional coating type - Acktar Diffusive White™ – was also measured to characterize its cryogenic performance. For Acktar Fractal Black™, an effective coating thickness can be realized dependent on its intended temperature range. To aid that, an an empirical model was also developed illustrating the emissivity performance of the coating at various temperatures. The measured emissivities of Acktar Diffusive White™ were lower but comparable with Fractal Black™. High thermal stability of spectrally flat Ackar Fractal Black™ was successfully demonstrated as it was cycled between 5 K - 300 K without any visible sign of degradation.

INTRODUCTION

Materials in space applications are subjected to harsh environmental conditions such as high vacuum, thermal cycling, micrometeoroid particles, UV, proton-, electron- and electromagnetic irradiation, exposure to atomic oxygen (ATOX) and complex mechanical conditions [1]. Cryogenic considerations are an essential part in the design and development of current and past space flight instrumentation as shown in a review by Collaudin et al [2].

Thermal radiation – particularly emissivity – plays a crucial role in heat transfer at cryogenic temperatures: whether dissipating the heat away from the cryogenic system [3] or suppressing thermal radiation to minimize heat leak into the system, thermal radiative properties of materials are of significant importance [4]. Thermal design and the functional properties of the surface highly depend on its radiative properties, which are influenced by various factors e.g. material composition, temperature and surface topology [5], [6] making it very difficult to rely on numerical/analytical predictions. Hence, it is vital to experimentally – in an accurate and repeatable way – determine emissivity and absorptivity at cryogenic temperatures. The main challenge associated with empirical measurements is the ability of the thermal radiator to emit power at such low temperatures [4]. Sample emissivity measurements – at various temperatures – can be divided into two categories: calorimetric methods and radiometric methods as detailed by Králík et al. [7].

The calorimetric method is based on a radiator and an absorber, where the total hemispherical emissivity of the material is calculated from the heat detected transferring between them. It is a commonly used and simple method where the sample can be used both as a radiator and an absorber if the radiative property of another part is already known. An example of this is demonstrated by Tuttle et al [8] who used such a calorimetric method to measure the thermal absorptance of a gold-plated steel tubing exposed to thermal flux at various temperature levels. The experiment was carried out in order to confirm that the mechanical cryocooler can meet the requirements (minimal emissivity) of the Mid Infrared Instrument (MIRI) on the James Webb Telescope. The radiometric method, on the contrary, is a more complex way of measuring radiative properties. It requires a reference blackbody to compare against when measuring emitted/reflected radiation, however it yields the results faster and the spectral emissivity can be also measured [4].

Black coatings have been widely used in space applications and ultra-sensitive missions where high emissivity surfaces are required due to their ability to maximize radiation cooling to maintain cryogenic temperatures of the optical sensors and to reduce thermal noise [9]. A proprietary deep black coating developed by Acktar, Fractal Black™ can not only minimize reflectance in a wideband spectrum - from ultraviolet (UV) and visible (VIS) through far-infrared (FIR) - ensuring accurate optical measurements and reduced signal to noise ratios [10], but also effectively controls thermal radiation across spacecraft components. This is also underpinned by the application of Fractal Black™ in satellite-borne optical instruments such as the James Webb Space Telescope (JWST) or space missions such as the Bepi Colombo mission to Mercury [11]. In fact, Fractal Black™ was selected by the European Space Agency (ESA) as a reference material to be directly exposed to space environments on the Euro Materials Ageing Experiment, as part of the "Bartolomeo 'front porch' attached to Europe's Columbus module aboard the International Space Station" [12].

The emissivity of various black coatings on flat surfaces was measured using a calorimetric method and compared with a black coated open honeycomb surface at 20 – 80 K [9]. It was found that the emissivity of the coated flat surfaces was highly dependent on temperature. When transitioning from ambient to cryogenic temperatures, the emissivity performance of black surface coatings can decrease significantly, especially – as per Wien's displacement law – the dominant wavelengths of infrared radiation become longer with decreasing temperature. In another study by Adibekyan et al [13], the directional spectral, directional total and hemispherical total emissivity of four widely used black coatings – Nextel 811-21, Herberts 1534, Aeroglaze Z306 and Acktar Fractal Black™ were examined. The highly accurate measurements were carried out in a temperature range of 25°C to 150°C and at various wavelengths from 4 µm to 100 µm. In the study presented here, the emissivity performance of Acktar Fractal Black™ is examined at cryogenic temperatures down to 15 K (-288.15°C). The total hemispherical emissivity (ε) of Acktar Fractal Black™ is measured using a calorimetric method developed by Králík et al. [7]. The deep black coating developed by Acktar is applied in various thicknesses of 20, 35 and 45 µm respectively to investigate the effect of coating thickness on the emissivity performance.

EXPERIMENTAL

Methodology & Apparatus

In the following, a brief explanation of the methodology for the measurement of total hemispherical emissivity (ε) is given. For a detailed explanation, the reader is referred to the study by Králík et al. [7].

The calorimetric method utilized is based on the measurement of radiative heat power Q_R [W] transferred in vacuum between two mutually parallel and concentric discs (Ø 40 mm), separated by about a 0.5 mm gap. A schematic cross-section of the 'Emister' instrument developed at ISI Brno [7] is illustrated in Figure 1.

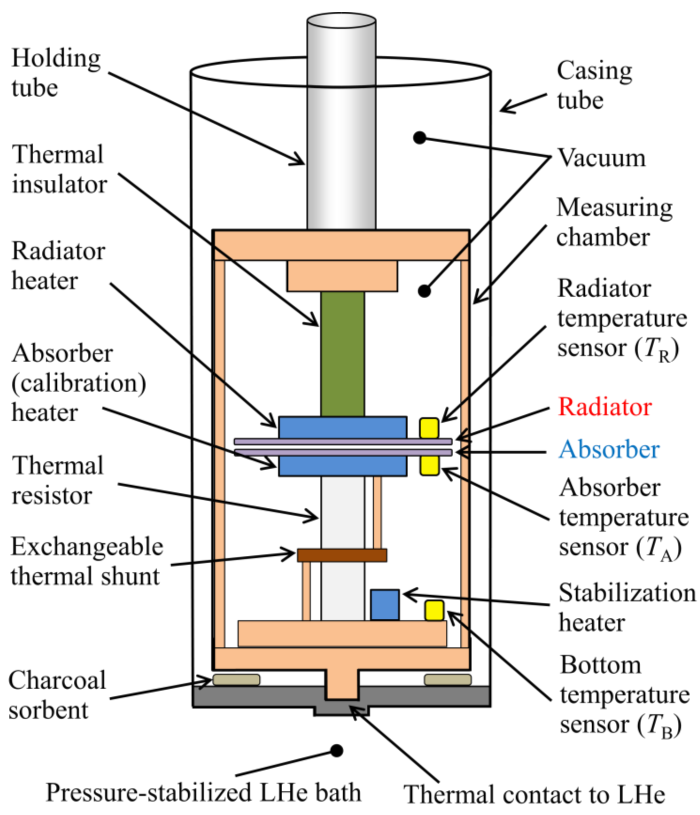

Figure 1. A schematic cross-section of the measurement chamber 'Emister' [7]

The examined sample is located at the position of radiator (temperature T_R), which is kept at temperatures higher than the opposite disc (absorber at temperature T_A). The absorber disc is used as the reference, having very high absorptivity and emissivity which is approximately 94 % of the value of T_R above 50 K. The reference disc is thermally connected to the liquid helium (LHe) bath via a thermal resistor, i.e., heat flow meter (HFM).

The sample as well as the reference disc is placed inside a measuring chamber housed in a stainless-steel casing tube, which, after evacuation, is inserted into a commercial wide neck LHe Dewar vessel. During the measurement the vacuum is passively kept by a cryopump at a level lower than 10^{-7} Pa. For the measurements, a LakeShore 340 type temperature controller was used together with LakeShore™ type temperature sensors: Cernox™ CX 1050 for measurement of T_A as well as T_B (measured at the bottom of the HFM) and LakeShore™ DT470 SD silicon diode for the measurement of T_R respectively.

Measurement procedure and evaluation

After the samples were placed in the measurement chamber, the apparatus was cooled down to about 5 K. For each sample disc that was tested, various setpoints were established, at which - after reaching thermal equilibrium temperatures – the T_R (radiator), T_A (absorber) and T_B (bottom of the HFM) were measured. The heat flow was measured as the temperature drop on a calibrated thermal resistor linking the absorber with the LHe bath.

As described previously in [7], the final emissivity of the sample can be calculated as a ratio of the measured radiative heat power Q_R and the heat power Q_B that would be exchanged between two black bodies with 100% emissivity (absorptivity) as described in Equation 1.

$$Q_B = A \cdot \sigma \, (T_R^4 - T_A^4) \tag{1}$$

, where A denotes the sample area and σ the Stefan-Boltzmann constant respectively.

Sample design

All samples consisted of a tailor designed, CNC machined, Ø 40 mm diameter Aluminum 6061 substrate disk that was coated prior to the measurements. Acktar coatings™ were applied to the disks using a proprietary vacuum deposition technology. Three different thicknesses were deposited using Fractal Black™ to investigate the effect of coating thickness on the emissivity performance at cryogenic temperatures. Furthermore, a new product, Acktar low-emissivity White™ / Diffusive White™ was also applied to a specimen for characterization purposes. A summary and an illustration of the prepared samples is shown below in Table 1 and Figure 2 respectively.

Table 1. List of the samples tested for total hemispherical emissivity

Sample ID	Sample format	Substrate material	Coating type and thickness
P#14062_2	Disc	Aluminum alloy 6061	Fractal Black™ 20 µm
P#14062_3			Fractal Black™ 30 µm
P#14062_4			Fractal Black™ 45 µm
P#14062_5			Acktar Diffusive White™ 15 µm

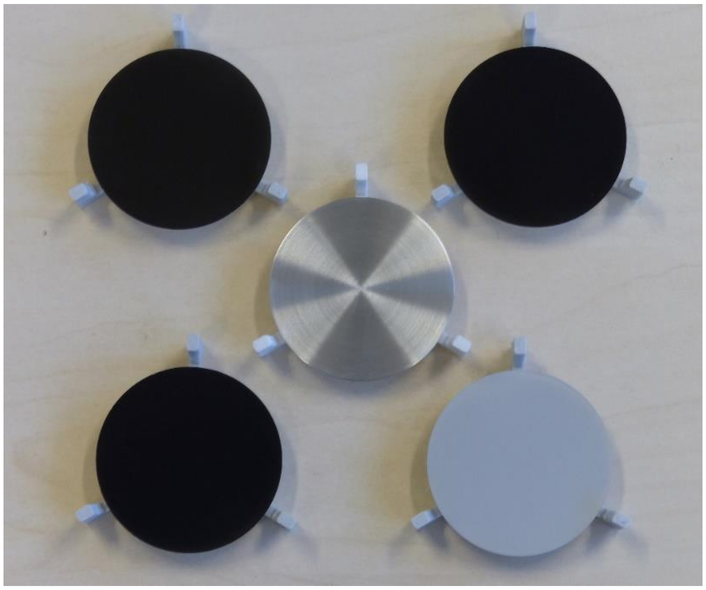

Figure 2. Illustration of tested samples with various Acktar coatings. From upper left to lower right corner, the samples with the Fractal Black™ coating (20, 30 and 45 µm) followed by the disc with the Diffusive White™ coating (15 µm) are shown. In the middle an example of the Al alloy disc is exhibited. Identical metallic discs were used as the substrate surfaces for all the presented coatings.

RESULTS AND DISCUSSION

The dependence of total hemispherical emissivity (ε) on the temperature of the thermal radiation T_R was obtained as shown in Figure 3. Experimental data are presented at selected temperatures of the tested samples ranging between 15 K – 300 K.

All the samples exhibited a gradual increase in total hemispherical emissivity as temperature increased, reaching relatively high absolute values between 60%-90% for most intervals. For T_R lower than about 50 K, the measured emissivity values dropped significantly with the decreasing surface temperature. This effect can be contributed to the partial transparency of the coating for very long wavelengths in the spectrum of black body radiation. When comparing the emissivity values at selected temperatures (T_R) for the distinct Fractal Black™ coated samples, it can be seen that the increase in emissivity is not linear with the increase of the coating thickness. When compared, the coating thickness increases by about 30% for each sample. The emissivity increase was in the range of 30% - 4% (the highest difference being at low temperatures) when comparing the 30 µm specimen to the 20 µm one, whereas the difference in the emissivity between the 45 µm specimen and the 30 µm one exhibited a much narrower gap. This finding can be used to find an effective thickness of the coating for the intended temperature range where it will be used. Furthermore, an empirical model was also realized to aid the optimization of finding such an effective thickness as it is shown in Figure 3.

The measured emissivities E_1 of Fractal Black™ and Diffusive White™ in Figure 3. are empirically fitted by function (2) and function (3) respectively, where T_R represents the temperature of the sample and a, b, c are fitting coefficients.

$$E_1 = -a\left(e^{-\frac{T_R}{b}} - e^{-\frac{T_R}{c}}\right) \tag{2}$$

$$E_1 = a\left(e^{bT^c}\right) \tag{3}$$

The sample coated with 15 µm thick Acktar Diffusive White™ exhibited lower emissivity values when compared to Fractal Black™ at cryogenic temperatures. However, at room temperature, the measured emissivities were comparable with other measurements on Fractal Black™.

To compare with the currently measured data, Figure 3. also presents the emissivity curves of a Diamond-like carbon (3.3 µm) and Chemglaze Z306 coating (55 µm) respectively, measured earlier by the same methodology. Diamond-like carbon is a class of amorphous carbon material with high hardness and wear resistance, while Chemglaze Z306 is a polyurethane coating with high solar absorptivity and emissivity. The Diamond-like carbon was deposited on a smooth copper substrate. As seen in Figure 3, both alternatives exhibited lower emissivity values when compared to measured Acktar Fractal Black™ coatings.

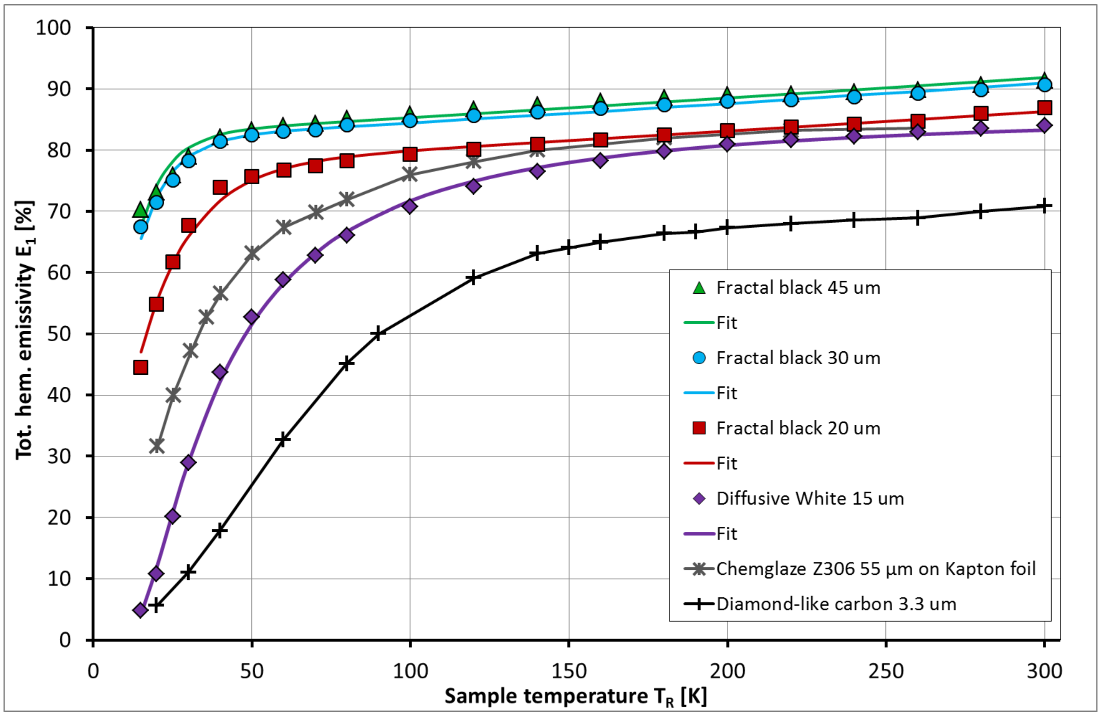

Figure 3. Dependence of total hemispherical emissivity on the temperature of thermal radiation (T_R). The lines represent the empirical fits of the measured data (Eq. 2 and 3).

CONCLUSIONS

The total hemispherical emissivity (ε) of Acktar Fractal Black™ was measured using a calorimetric method. The Aluminum alloy disc substrates were coated with three different thicknesses of Fractal Black™: 20, 35 and 45 µm respectively to investigate the effect of coating thickness on the emissivity performance especially at cryogenic temperatures.

The reflectivity of the surface (coating) limits the absorption/emission of the sample. It was found that the increase in coating thickness did not correlate linearly to the increase in emissivity. In fact, data suggests a limit at which an effective coating thickness can be realized dependent on the intended temperature range. As emissivity is dependent on the temperature of the source of thermal radiation (spectrum) [14], this is also connected to the partial transparency of the coating at cryogenic temperatures where the spectrum distribution is as such that the longer wavelengths of IR radiation can better penetrate the layer to the substrate. This is the reason for the significant change in the emissivity below 50 K whereas for increasing temperatures (above 50 K) such drastic change is reduced. Hence one can conclude that black coatings such as Ackar Fractal Black™ exhibiting a spectrally flat like behaviour are of high interest as they provide thermal stability which is essential in space applications. The high thermal stability of Ackar Fractal Black™ was also demonstrated successfully during the presented measurements: the deep black coating withstood a cool down to 5 K and warm up to 300 K without any visible sign of degradation.

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