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Examination of metallic surfaces for IR gray body sources

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Abstract

Measurements of 2D microbolometric detector arrays as well as pyrometers and multispectral IR devices require new-type standard sources of thermal radiation. The paper presents investigation results on efficient emissivity of diffusion surfaces, vacuum deposited with a gold layer, used for radiators construction. It reduces radiator costs and limits a number of radiators made of various construction materials. Dissipative surfaces were obtained using anisotropy mechanical treatment. The measurement results of roughness parameters of the tested surfaces obtained with optical and mechanical methods are given. Angular distribution of emissivity has been determined. The carried out measurements confirmed the possibility of production of a surface of expected emissivity.

1. Introduction

Demand for standard sources of thermal radiation of a new type has appeared together with development of construction of 2D microbolometric detector arrays and devices for contactless measurement of temperature, employing improved methods of multispectral pyrometry. The sources useful for such applications are equipped with radiators of defined emissivity, lower than 1.

Especially high demands have to fulfill the sources used for investigations of detector arrays. For such measurements, the sources of uniformity higher than temperature resolution (discrimination) of arrays should be used. Such sources provide a sensitivity measurement and estimation of efficiency of elimination methods of sensitivity nonuniformity of single detectors in a bolometers array. To obtain very high uniformity of spatial distribution of IR power, the Ulbricht Sphere is used. Inside of such a ball it is a dissipative surface ensuring multiple reflections of radiation from external IR radiator (IR source). About the Ulbricht Sphere quality decides its energetic efficiency. In IR range, high efficiency can be obtained choosing adequately a material for deposition of a dissipative surface. Typically, in noncontactless measurements of temperature, the cavity absolute blackbodies are used. However, for investigations and calibration of two-, three-, and multispectral pyrometers, the standard gray bodies with radiators of determined emissivity are needed [3, 6]. Due to application of such a source, determination of its own values and testing algorithms of processing measuring data [2] are possible. In measuring systems with gray sources, the accuracy of temperature measurement with consideration of background radiation can be estimated [4]. In such applications, very useful is the possibility of application of surfaces having the known emissivity in the range of $0.5<\varepsilon<1$.

2. Selection of materials and technologies for surface finish

2.1 IR sources of high uniformity of radiation density

IR radiation introduced into the Ulbricht Sphere, e.g., from a cavity blackbody, should undergo multiple reflections. Thus, it is not permissible the fact, that input beam leaves the output aperture after a single reflection. To avoid such a situation, additional reflecting elements are used in the input aperture of the Ulbricht Sphere and the Sphere's inside is mechanically treated to obtain strongly dissipative surface. Such a surface is covered with materials of high reflection coefficient. The chosen covering material decides on energetic efficiency of the device. In a visible range, there exist a series of materials fulfilling the requirements for reflection and diffusion scattering coefficients, but in IR range selection of materials is limited. It results from the fact that IR is strongly absorbed by majority of materials. Moreover, the roughness values have to be significantly higher than that in visible range because the lengths of wavelengths in IR are of one order higher. Materials of high reflection coefficient and very rough surface are indispensable to obtain diffusive surface of high quality. Metals are the materials which can be used for this purpose. Since the investigated IR devices, additionally to a measurement of radiation intensity make also an analysis of spectral parameters of radiation, in precise measurements it should be taken into account that metals are not gray bodies. However, their spectral emissivity slowly changes as a function of wavelength. In a long wavelength range of a spectrum it is described by Hagen-Rubens relation. In the range of shorter waves, it is also a function of the inverse of a root of wavelengths, while the constant coefficient in this function has to be determined experimentally [3] every time. The polished metal surfaces characterize with low emissivity coefficient and their reflection coefficient is described by a relation.

$$\rho = 1 - \varepsilon \tag{1}$$

For low values of the emissivity ε, the reflection coefficient reaches high values close to 1. Especially good material is gold, the polished surface of which characterizes with the emissivity ranging from 0.01 to 0.05 [5]. Radiation scattering in the Ulbricht Sphere, covered with gold, is obtained due to adequate mechanical treatment of its internal surface. The treatment has to ensure sufficiently high roughness of this surface.

2.2 IR gray sources (2)

Radiation sources of the known, stable in time, emissivity ε < 1 can be built using cavity radiators of adequately chosen geometry. Practical realization of such a source is discussed in [4]. It is multi-cavity radiator in which radiating cavities are the cones of suitably chosen configuration coefficients Fc. For the assumed base diameter D, the configuration coefficient Fc was changed by adequate selection of the cone height H.

$$Fc(H, D) = 1 - \frac{1}{\sqrt{4\frac{H^{2}}{D^{2}} - 1}} \tag{3}$$

For the cone made of material of the known emissivity ε, the efficient emissivity is [1]:

$$\varepsilon_{eff} = \frac{\varepsilon}{1 - (1-\varepsilon)F_c} \tag{4}$$

Choosing suitably the configuration coefficient of radiating cavity, the efficient emissivity ε_{eff} can be changed in a wide range. Linear approximation of the efficient emissivity vs. a configuration coefficient has a form:

$$\varepsilon_{eff} \cong \varepsilon + (1-\varepsilon)\cdot\varepsilon\cdot F_c \tag{5}$$

It results from Eq. (4) that minimum emissivity is equal to material emissivity ε, - the case of plane surface (Fc ≅ 0). To have the possibilities of making radiators of wide range of changes of efficient emissivity, low emissivity of initial material is required. A group of materials fulfilling this condition are metals. Selecting adequate from them, such as gold, nickel, and chromium, long-lasting stability of the emissivity coefficient can be obtained. It results from resistance of these metals to the atmosphere influence. A radiation source, discussed in [4], was used for investigations of multi-wavelength pyrometer. Thus, output diameters of radiators were relatively small and amounted 25 mm (1"). For universal device used not only for pyrometers investigations but also for thermal cameras, the output diameters should be significantly larger, of the order of 100 mm. Having in view a low emissivity of the cone material, for such diameters the value of efficient emissivity near unity would require large dimension devices. A solution of this problem is increase in emissivity of radiating surface with no change of material. To obtain the higher emissivity, additional mechanical treatment increasing surface roughness should be applied.

3. Measurements of roughness parameters

A relation between emissivity of mechanically treated surface and roughness of such a surface is not, in general, described analytically. It results from the fact that it is a function of high number of technological parameters that are difficult for analytical description. It relates to both mechanical treatment (e.g., grinding) and the parameters of this treatment (e.g., velocity of a material shift). Thus, selection of the process and parameters of surface treatment has been proposed on the basis of general indications, related to the required (expected) final state of the surface.

Radiation emitted or reflected from a surface should have uniform spatial distribution in a wide angular range. Such a phenomenon occurs when the surface roughness is anisotropic and has stochastic character. Such requirement limits a number of technologies that can be used. The technologies causing deterministic character of roughness cannot be applied, e.g., machining. On the basis of initial trials, the method of metal surface matting (tarnishing) by means of sand-blasting with electro-corundum powder has been chosen. The process parameters were selected experimentally. In dependence of the used diameter of powder grains, the surfaces of various roughnesses were obtained (Table 1). For assumed geometrical parameters of the Ulbricht Sphere, its theoretical

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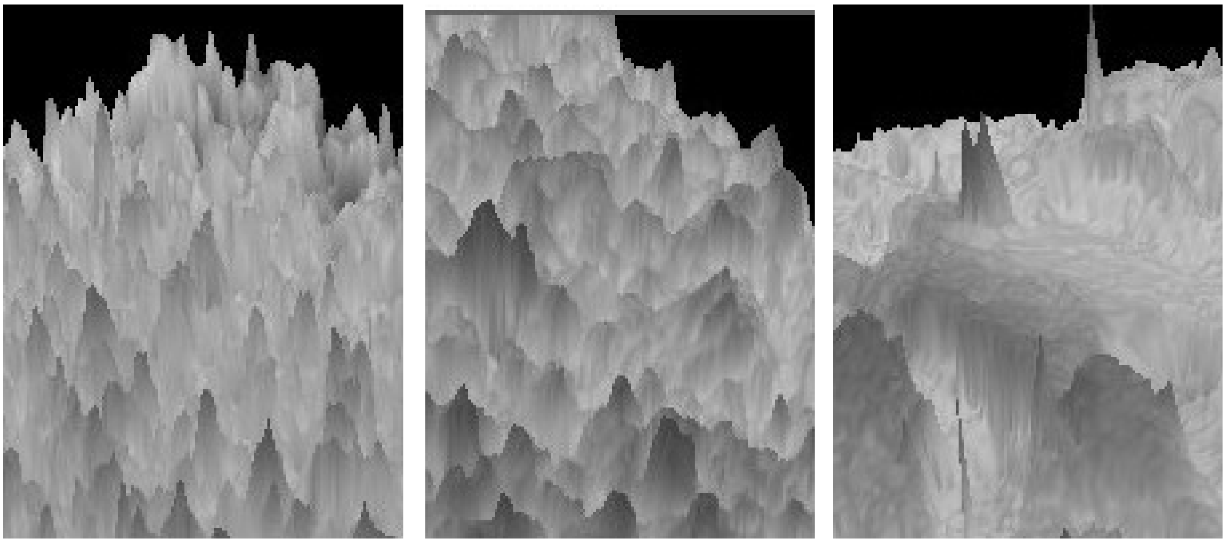
energetic efficiency has been determined using Zemax program. Assuming aluminium dissipative surface, it was 4.2 %. For thermal cameras calibration, it should be no fewer than 2%. Such efficiency can be obtained when gold will be vacuum deposited on the Sphere surface. Similar technology has been applied for cone radiators but the substrate was made out of aluminium alloy foil.

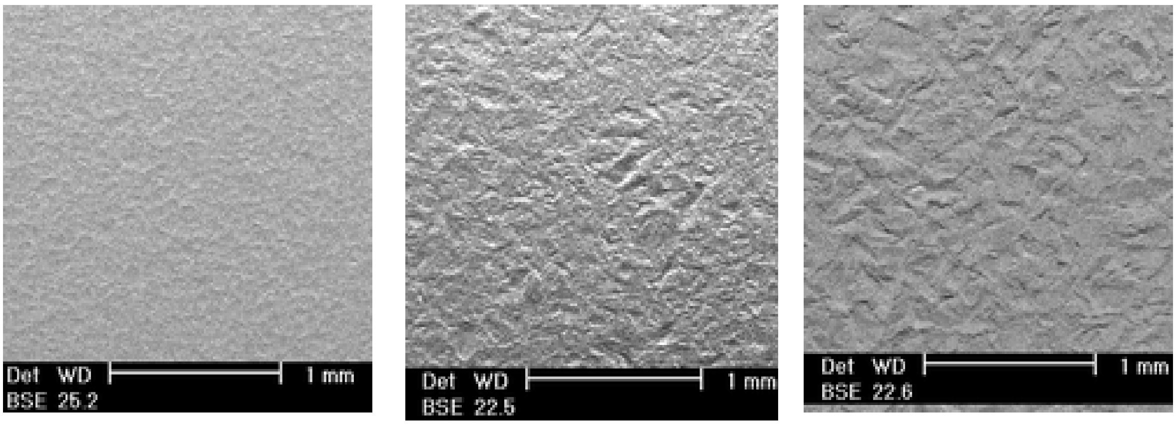
As a result of vacuum deposition of gold, the radiator surface of a roughness resulting from sand-blasting parameters has been obtained. Three plane test samples were made for investigations of dimensions $30\times60\ mm^2$. A value of the average roughness Ra of these samples increases twice between subsequent samples (Table 1). The samples roughness has been measured using two independent methods. The first measurements, because of low mechanical resistance of gold layer, were made contactless using Veeco NT1100 optical profilometer. The surface maps performed with optical method are shown in Fig. 1.



Au1 Au2 Au3

Fig. 1 *Maps of surfaces of test samples performed on Veeco NT1100 optical profilometer.*

For comparison, the roughness measurements were performed also using PGM-1C mechanical profilographometer. This method is applied at IOE MUT as a standard one. The obtained results have been compared with these obtained on optical profilometer. To estimate qualitatively the sand-blasted surfaces, they were observed using scanning electron microscope (SEM). Such observations were carried out both in a standard mode as well as with back scattered electrons emission (BSE). SEM images presenting topography of the surfaces of sand-blasted samples are shown in Fig. 2.



Au1 Au2 Au3

Fig. 2 *Surface morphology obtained with electro-corundum power blasting.*

An analysis of geometrical structure of a surface, due to measurement of roughness and wavy finish in 2D and 3D system by means of PGM-1C profilographometer, showed that roughness of all investigated surfaces is of random and isotropic character. Exponentially decaying autocorrelation functions testify to it, but it can be

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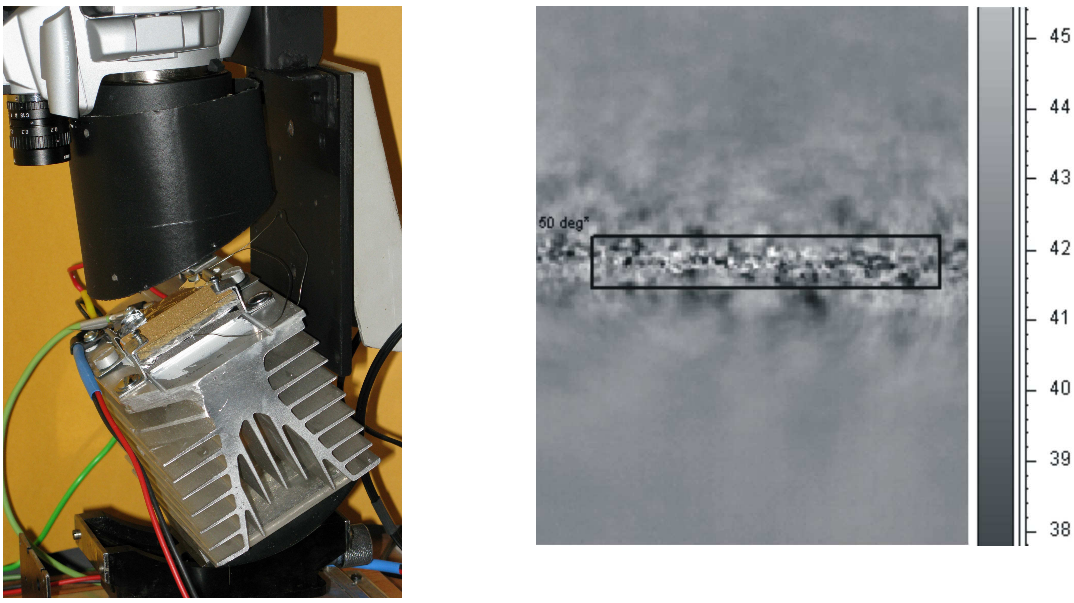
observed for each analyzed case of surface treatment, that periodical components appeared, having random character, that are caused by treatment process disturbances such as non-uniform shift of a nozzle in relation to the surface, variable angle of impact of particles with a surface, and variable distance between a nozzle and a surface. Other factors testifying to isotropy of the investigated surfaces are the courses of spectral power density having character of random noise. Basic amplitude parameters of surface roughness, determined from spatial profiles for the analyzed samples, are given in Table 1. Also the parameters of electro-corundum grains used for performance of a determined surface are presented.

***Table 1**. Roughness parameters of tested surfaces.*

Sample		Au-1	Au-2	Au-3
Grain size (Al2O3)		24/850/710	22/1000/850	16/1400/1180
Roughness parameters	SRa [µm]	5.27	8.98	11.63
	SRz [µm]	53.99	95.04	110.93
	SRq [µm]	6.71	11.37	14.72

4. Investigations of radiant properties of surfaces

Measurements of emissivity of sand-blasted metallic samples were made with a thermographic method using ThermaCAM P640 camera. For stabilization of their temperature, a thermostat with Peltier module and temperature controller PID was used. It provided the temperature setting in the range from dew point (saturation point) temperature up to 95^{o}C with the accuracy of 0.1^{o}C. For measurement of a sample temperature and ambient temperature, electronic thermometers were used with platinum resistors Pt100. To decrease influence of the reflected radiation of a background on thermographic measurements, the investigated sample was kept at the temperature higher than the ambient temperature. All the presented measurements were made for the samples' temperature equal to 93^{o}C. On the basis of the data contained in the thermogram and the information on the sample temperature and background temperature, the efficient emissivity of the sample has been determined. A view of the investigated sample on a measuring stand is shown in the picture, Fig. 3(a). To show a way of sample holding, additional thermal housing was removed. Exemplary thermogram for the sample situated at the angle of 40 degree to the normal direction vs. the sample surface is given in Fig. 3(b). The fragment of a diffusion surface for which an efficient emissivity was calculated is marked with a rectangular frame. For large inclination angles of the sample, the area of sharp reproduction takes a shape of a narrow rectangle. It is connected with application of the objective allowing for performance of thermograms in macro mode. In such a mode, a depth of field is of small area, so each time the measuring field was determined at the same place. Left limit of this field covers with the fragment of the sample surface under which a sensor of its temperature was located



a) b)

***Fig. 3**. Measuring stand (a) and thermogram for the sample situated at the angle of 50^{o} (b).*

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Calculations of emissivity were made using ThermaCAM Researcher Pro 2.7 program. Surface roughness is a parameter in micro scale. Thus, measuring area – a camera field of view should be small. It has been obtained by application of close-up type objective. The nearest neighbourhoods of the investigated sample and objective, as well as the camera's objective were covered additionally with a diffusion screen of black surface. It ensured stable measuring conditions. Additionally, the effect of heat exchange with environment through convection was reduced. Background radiation, from a screen was constant during the measurement. Influence of a background was compensated by thermal camera settings. A value of correction was calculated on the basis of the temperature inside a measuring node. Table 2 presents the emissivity values for a normal direction α=0, α=20°, and α=45° for particular samples.

Table 2. *Emissivity of measured surfaces.*

Sample	Au-1	Au-2	Au-3
Roughness SRa [μm]	5.27	8.98	11.63
Emissivity α=0°	0.18	0.23	0.28
Emissivity α=20°	0.19	0.22	0.27
Emissivity α=45°	0.19	0.22	0.28

Angular distribution of the emissivity results from a mutual spatial configuration of nozzles and sample and shift direction of a sample during the sand-blasting process. Too large change of emissivity vs. angle can be a reason of non-uniform energy distribution in the area of the output aperture when such surface is used in the Ulbricht Sphere. Because of it, emissivity characteristics were measured as a function of an observation angle. The results are shown in Fig. 4.

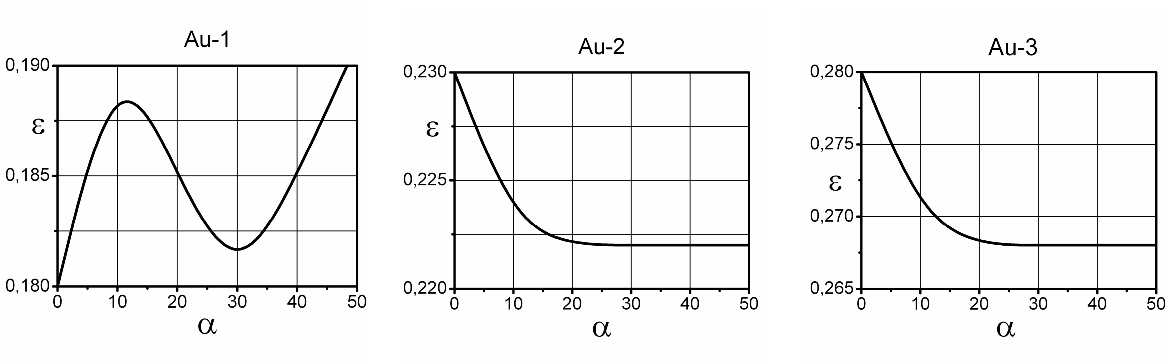

Fig. 4. *Angular characteristics of emissivity of sand-blasted metal samples.*

For Au-2 and Au-3 samples, the angular distribution of emissivity is consistent with the expectations. It decreases of fewer than 2% for the angles larger than 20^o and next it stabilizes. For Au-1, comparable decrease in emissivity is observed but for the angles ~30^o. However, local extremes can be seen. Such a course of the function describing emissivity results from the fact that the sample was treated simultaneously by means of two crossed nozzles.

5. Conclusions

IR sources should characterize with uniform density of emitted radiation in the whole active area of radiating surface. Such sources can be used for calibration and testing of IR devices of various fields of view (FOV). As materials for radiating cavities, metal surfaces can be used having adequately chosen roughness class. This roughness should be anisotropic and its superficial distribution should be stochastic one. The tested method of the roughness obtained by means of sand-blasting ensures such character of surface topography. Simultaneously, a change of roughness is technologically simple and consists in a change of grains diameter of sand used for surface treatment. Due to a change of roughness, it is possible to obtain variable values of base emissivity, i.e., for a plane surface. Final, efficient emissivity results from a shape of the radiator's cavity. Especially good material for making gray sources and sources of high radiation uniformity is gold. High reflection coefficient ensures low radiation attenuation for multiple reflections in the Ulbricht Sphere and the possibility of obtainment of emissivity values in a wide range for gray radiators. In the tested samples, gold was vacuum deposited on a substrate of determined roughness. Thin film of gold kept optical properties of gold, simultaneously reproducing a surface topography. Due to it, the cost of radiator can be reduced and the number

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of various construction materials can be limited. The performed measurements confirmed the possibility of performing surfaces of the expected emissivity.

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