Emissivity of aluminium and its importance for radiometric measurement

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Abstract. *In the article, the authors analyse features of aluminium, which are important for the non- contact measurement of the temperature. This study is based on the results of experiments, which were carried out at foreign research institutes. Rising interest of the industry in contactless measurement of foamy aluminium profiles during their production was the motivation for this article.*

Key words: *reflectivity, absorbance, transmittance, emissivity.*

1. Introduction

Aluminium and its alloys belong among the most frequently used metals of these days. Mechanical features of aluminium depend on its purity, structure, and previous mechanical and temperature processing. Rust resistance of aluminium increases with its purity. Aluminium is stronger after cold processing. Alloys of aluminium (Al-Cu-Mg duralumin - Dural 17S, 22S 24S) are used more frequently than aluminium itself, mainly because of its low weight coefficient, good mechanical features, good machinability, toughness, good pourability (alloys of Al-Si), rust resistance (alloys Al-Ti-Mn). Aside to the production of pipes, rods, plates, forgings, wires, foils, painting masses and various profiles, significant using of aluminium plays a key role in the production of mirrors for ultraviolet, visible and infrared radiation (mirrors for full sky cameras, space glass, mirrors of projectors, thermo vision cameras).

Radiometric – contactless methods of measuring the temperature are commonly used in technological processes of iron, fabrication of alloy, production of steel and some non-ferrous metals, but this type of measuring of temperature is not usually employed in the production of aluminium and its alloys. This is caused by the emissivity of aluminium that is, in comparison to emissivity of iron, very low [1]. Emissivity of aluminium is because of this discussed as a basic parameter that characterises capability of radiation of the material.

2. Optical features of substance

Radiant flux, which falls the surface of some body, is partly reflected, partly transmitted and the body absorbs part of it. In optic we characterise reflectivity of a surface ρ, transmittance τ and absorption α. Generally

$$\rho + \tau + \alpha = 1 \tag{1}$$

For opaque body is $\tau = 0$, so absorption of substance is $\alpha = 1 - \rho$. In assumption that radiation of body is during thermodynamic balance with surroundings, then in accordance with the Kirchhoff's law [2] for spectral emissivity $\varepsilon(\lambda, T)$ of body equals:

$$\varepsilon(\lambda, T) = \alpha(\lambda, T) = 1 - \rho(\lambda, T) \tag{2}$$

Refraction index of substance $\boldsymbol{n} = c_o / \boldsymbol{c}$ is in general complex quantity, where c_o is speed of light in vacuum, $\boldsymbol{c}$ is complex speed of electromagnetic wave in the substance. That means, that complex refraction index **n** is

$$\boldsymbol{n} = n - j\kappa \tag{3}$$

Where n - real part is refraction index of substance, $\boldsymbol{\kappa}$ – imaginary part is constant of absorption of substance, $j = \sqrt{-1}$ is imaginary unit.

Among optical quantities n, κ and electromagnetic quantities that characterise quality of substance, electrical conductivity χ, permittivity E, permeability μ equals:

$$n^2 - \kappa^2 = \frac{E.\mu}{E_o.\mu_o} \;;\; n.\kappa = \frac{\chi.\mu}{\omega.E_o.\mu_o} \tag{4}$$

Where $\omega = 2\pi\nu$ and ν is frequency of radiation, E_o, μ_o are permittivity and permeability of vacuum.

Considering the emissive view of the features of material, there are interesting especially two types of body.

A. If $\chi << 2\pi\nu E$, what is typical for dielectrics and for radiation of very short waves (RTG radiation), is value of quantity $\kappa << n$, so complex index of refraction contents just from real part

$$\boldsymbol{n} = n = \sqrt{\frac{E.\mu}{E_o\mu_o}} \tag{5}$$

In this case electromagnetic oscillation propagates in non absorb substance, in which speed of electromagnetic radiation decreases and wavelength is shorter, with increasing index of refraction. For non-ferromagnetic substances $\mu \sim \mu_o = 4.\pi.10^{-7}$ H.m^{-1}.

B. In the case when $\chi >> 2\pi\nu E$, what is typical for materials with high conductivity like metals, or for radiation of longer wavelength, the real part of complex index of refraction equals to imaginary part [3]

$$\kappa = n = c_o\sqrt{\frac{\mu.\chi}{4.\pi.\nu}} = \sqrt{\frac{\mu.\chi.\lambda.c_o}{4\pi}} \tag{6}$$

Where we used relation $\nu = c_o / \lambda$.

Considering the results of Fresnell's formulas [2] for perpendicular incidence radiation to interface air – conduction area reflectivity is

$$\rho = \frac{(n-1)^2 + \kappa^2}{(n+1)^2 + \kappa^2} \tag{7}$$

Compared to relation after substitution and modification we have [3]

$$\rho \approx 1 - \frac{2}{c_0}\sqrt{\frac{4\pi\nu}{\mu\chi}} = 1 - 4\sqrt{\frac{\pi}{c_0.\mu.\lambda}} \tag{8}$$

If formula (2) is valid for opaque, then the emissivity

$$\varepsilon \approx 4\sqrt{\frac{\pi.r}{c_0.\mu.\lambda}} \tag{9}$$

Where $r = 1/\chi$ is specific resistance.

We can see from written formulas, that change of electrical conductivity of materials depends on the temperature of material and wavelength of radiation.

3. Relationship between emissivity of aluminium and wavelength

According to equation (8) we can see, that spectral normal reflectivity $\rho_{\lambda n}$ of opaque body with increased wavelength should increase and spectral normal emissivity $\varepsilon_{\lambda n}$ should decrease. Based on measuring of $\rho_{\lambda n}$ in the band from 0,22 μm to 0,38 μm and from 0,8 μm to 1,0 μm on layers of Al thickness > 50 nm evaporated to the glass substrate and on the experimental results written at work [4] this fact was confirmed (Fig. 1). Measuring used in this work was carried out on the cleaned polished surface 99,6 % Al with temperature T =295 K. Showed in both cases that reflectivity in the band (0,65-1,1) μm is local minimum with value of $\rho_{\lambda n}$ for λ = 0,82 μm. For the band from 0,2 μm to 10 μm is reflectivity > 0,9. This result affirms also graph in work [3] too

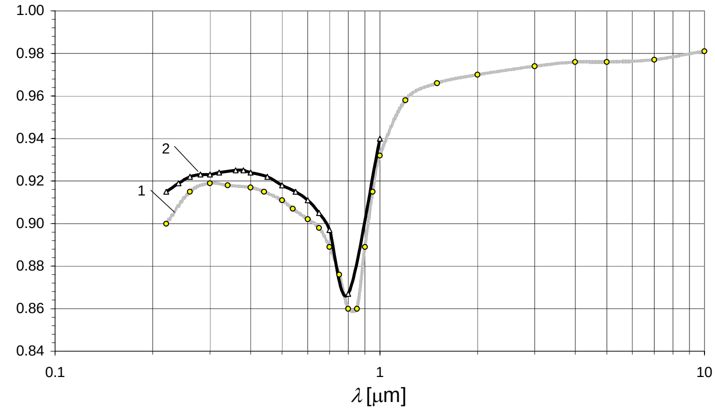

Fig. 1 Spectral normal reflectivity of aluminium at T = 295K
1 - values taken from literature [4], 2 - measured values

It is a well-known fact that the aluminium oxide, which protects aluminium from further influence of the atmosphere, covers the surface of aluminium. When exposed to the atmosphere, aluminium mirror creates a layer of 1 nm in 2 hours since it was produced. When using 99,98 % aluminium, a layer of 4,5 nm is created in 3 months. Natural layer of Al_2O_3 on the surface is 5nm. Speed of growing of the aluminium of trade purity 99,6 % was studied by Vernon [5]. From Vernon's results (Fig. 2), that on the aluminium of the trade purity can make layer of oxide up to 10 nm. It could be expected, that emissive properties of aluminium are influenced by natural oxidation of aluminium by the atmosphere. Significant change of reflectivity has plates of aluminium adjusted by eloxal coating. The spectral normal emissivity of the aluminium depends on wavelength changes with thickness of oxide layer [6].

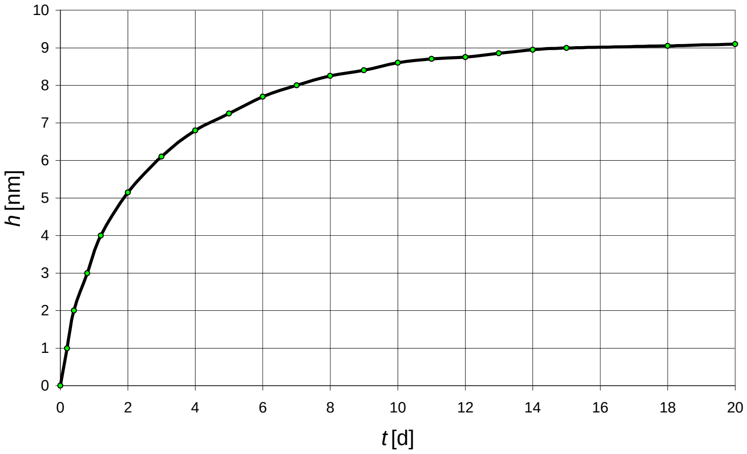

Fig. 2 Increasing of natural Al_2O_3 layer in dependence on time

Dependence of Al emissivity $\varepsilon_{\lambda n}$ on the wavelength from values converted according to (2) from measured values $\rho_{\lambda n}$ as showed in the Fig 1, is symbolized by curves 1 and 2 in the Fig. 3. Values symbolized by curve 3 in the Fig. 3. represents theoretical dependence of spectral normal emissivity Al on the wavelength in the band (0,1 - 10) μm calculated with approximate equation

(9) from values of specific resistance *r*, permeability $\mu = \mu_o$ and speed of light in the vacuum c_o. The physical interpretation of deviation in the spectral band (0,3 – 1,2) μm is unknown. Issuing of thin layer of oxide can cause lower values of the emissivity in the area of shorter wavelengths. Oxide layer of Al_2O_3 may not have any influence in the longer wavelength to the change of emissivity and for that reason values above 4,5 μm coincide. It is known that reflectivity of the eloxal coated mirrors are practically the same as of the mirrors not eloxal coated in the infrared area [6].

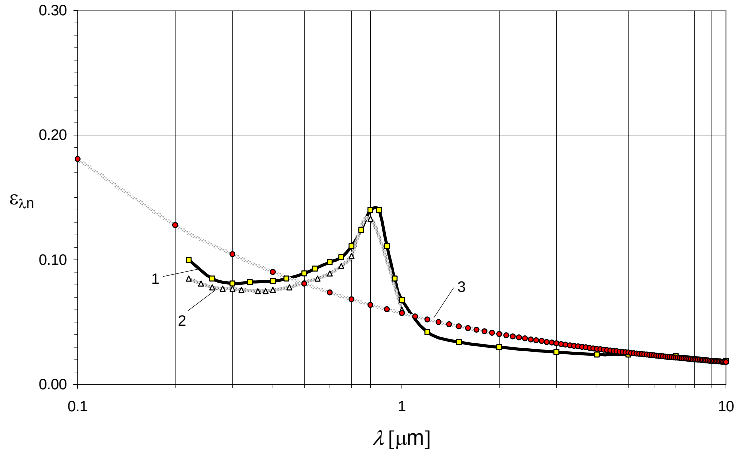

Fig. 3 Spectral normal emissivity of aluminium 1 - values calculated from measured reflectivity
2 - values calculated from data of reflectivity taken from [4]
3 - values calculated from (6)

Integral reflectivity of specular surface Al with thin layer Al_2O_3 is lower than pure Al surface. It is recommended [6] to make oxide layer of thickness 156 nm, for the best utilization of Al mirror in the visible part of spectrum with max. in λ = 550 nm. This layer effects like band spectral filter. Oxide layers adapted by eloxal coating by electrolyte, which dissolves nature layer of oxide are designed for surfacing of structural materials, they have thickness of Al_2O_3 layer above 500 nm and they have pores [6]. Transmittance of this layer is comparable with transmittance of white sapphire (pure Al_2O_3), which is in the band from 0,25 μm to 4,8 μm transparent [4]. Dependence of spectral normal emissivity on the wavelength of this adapted surface have irregular jumps in the band from 0,5 μm to 10 μm (Fig. 4). The values of emissivity were obtained by converting from process of spectral reflectivity that was presented in the work [5].

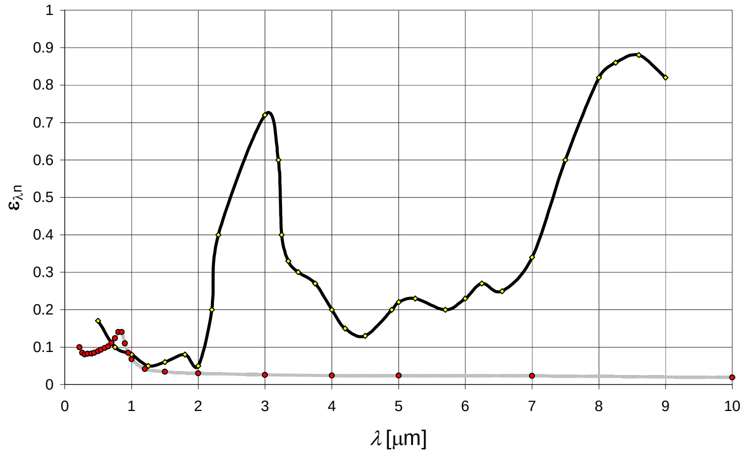

Fig. 4 Spectral normal emissivity of Al
1 - not eloxal coated
2 - thickly eloxal coated surface, taken from [5]

4. Dependence of emissivity of aluminium on the temperature

Emissivity of metal layer changes with changing of conductivity χ alt. resistivity *r*. Since conductivity χ of metals decreases with temperature, i.e. resistivity *r* increases with temperature, in accordance with (9) emissivity should increase with increased temperature. This is confirmed by the results of experiments that measured the dependency of integral hemispheric (Fig. 5) and normal integral emissivity on the temperature, as presented in the literature [4]. For hemispherical integral emissivity of Al was derived theoretical-empirical equation

$$\varepsilon(T) \approx 7{,}52(T.r)^{1/2} \qquad (10)$$

Where unit of *T* is [K] and unit of *r* is [Ω.m] and constant 7,52 has dimension $[\Omega.\mathrm{m.K}]^{-1/2}$. Consider, that in interval from laboratory temperatures to 50 K we can resistivity approximately express by equation $r = AT+B$, for considered interval of temperatures the value *B* is much low than *AT* and dependence of emissivity on the temperature is linear.
Experimental values of emissivities written in the table I. borrowed from literature [4] differs from values calculated from formula (10). We analysed validation of this formula.

Table I. Dependence of integral hemispherical emissivity Al on a temperature

T[K]	50	100	200	300	400	500	600	700	800
ε(T)	0,008	0,011	0,018	0,025	0,032	0,039	0,046	0,054	0,062

From experimental values written in the table 5,5-1 in [5] resistivity of aluminium 99,6 % pure in the interval of temperature from 0 °C to 400 °C can be approximately characterised by linear equation

$$r = 1{,}22.10^{-10}.T - 90{,}8.10^{-10} \qquad (11)$$

After substitution of *r* from (11) to (10) we have approximate dependence of hemispherical integral emissivity of aluminium

$$\varepsilon(T) = 8{,}3.10^{5}\,T - 3{,}4.10^{-3} \qquad (12)$$

According to experimental values written in the table I. from [4] dependence of hemispherical integral emissivity ε(*T*) 99,6 % Al on the temperature from 250 K to 800 K can be expressed by equation (see points on Fig. 5):

$$\varepsilon(T) = 7{,}2.10^{-5}.T + 3{,}2.10^{-3} \qquad (13)$$

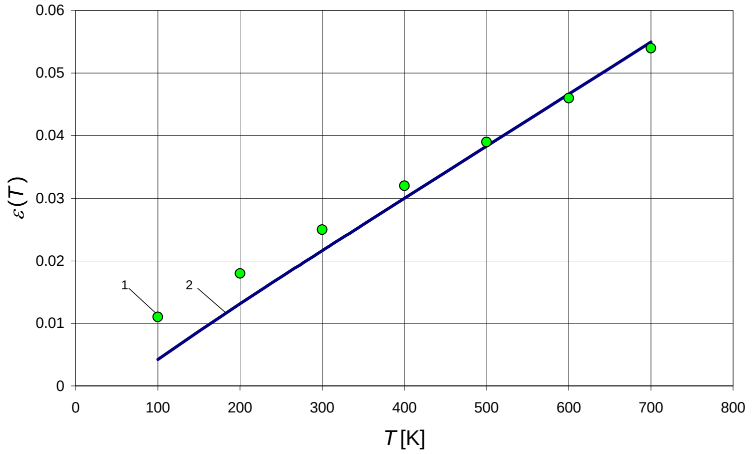

Fig. 5 1 - Experimental values of hemispherical integral emissivity
2 - Approximate dependence of hemispherical integral emissivity on temperature calculated from equation (12)

Alloys of aluminium with magnesium and silicon are tough and have high electrical conductivity. Resistivity of Al with 0,5 % Si and 0,4 % Mg is between $(0{,}03 - 0{,}33).10^{-6}\ \Omega.\mathrm{m}$, measured at temperature 20 °C . Resistivity increases with the increasing of content of silicon. For example an alloy with content of Si 5 %, at temperature 20 °C, has resistivity $(0{,}041 - 0{,}46).10^{-6}\ \Omega.\mathrm{m}$, while 99,997 % Al has resistivity $0{,}0263.10^{-6}\ \Omega.\mathrm{m}$ at temperature 20 °C. This means that emissivities of alloys of aluminium are higher, but still lower in comparison to other metals. As can be seen at http://www.electro-optical.com/bb_rad/emissivity/matlemisivity.htm, table Electro Optical Industries, Inc. and at http://www.instruments-gauges.co.uk/temperat/emiss.htm, table Instruments and Gauges Electronics, Ltd., emissivities for aluminium and some its alloys are generally low and near to emissivity of aluminium. Eloxal coated surfaces which are coloured, generally have higher emissivity.

5. Conclusion

Aluminium is very frequently used and its production rise steeply during the second half of the 20th century, but the emission of aluminium was not so far deeply analysed. It is indisputable, from written view that emissivity of aluminium and its alloys can be significantly increased by oxidation and by its paint over. This is applicable for production of coolers for electronic circuits, production of sun collectors and radiators. Vice versa, in cases where absorption of sun radiation and radiation of surface have to be lower, low emissivity of clean and polished aluminium is advantage. For example, aluminium paintings and tar paper with aluminium foil for flat roofs, outside of airplane, etc. This paper aims to present facts, which are important especially in the applications of radiometric methods of measuring of temperature of surfaces, where setting of correct value of emissivity is essential.

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