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Emissivity of Elgiloy and pure niobium at high temperature for the Solar Orbiter mission

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ABSTRACT

The science payload of the Solar Orbiter mission that will be launched in 2018 comprises the RPW (Radio and Plasma Waves) experiment that will perform in situ and remote-sensing measurements (magnetic and electric fields). Some parts of this instrument will be made of Elgiloy for the antennas and must be protected from the intense solar radiation by a heat shield made in niobium. Emissivity of both materials is important to know in order to correctly model before launch the heat transfer in the instrumentation. Hemispherical emissivity results in the two following wavelength ranges 0.6–2.8 and 0.6–40 μm are presented at temperatures up to 1500 K for these two materials according to their surface roughness particularly for the niobium samples and at room temperature in the wavelength range 0.25–25 μm. New original data are obtained for both the materials at high temperature.

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1. Introduction

The metallic materials characterized in this study will be used on the space Solar Orbiter mission, which is an ESA-led mission with NASA participation. Solar Orbiter is a mission dedicated to solar and heliospheric physics. Solar Orbiter will be used to examine how the Sun creates and controls the heliosphere, the vast bubble of charged particles blown by the solar winds into the interstellar medium. The spacecraft will combine in situ and remote sensing observations to gain new information about the solar winds, heliospheric magnetic field, solar energetic particles, transient interplanetary disturbances and the Sun magnetic field.

Scheduled for launch in October 2018, the mission will provide close-up, high-latitude observations of the Sun. Solar Orbiter will have a highly elliptic orbit between 0.9 AU (Astronomical Unit) at aphelion and 0.28 AU at perihelion. It will reach its operational orbit three-and-a-half years after launch by using gravity assist maneuvers at Earth and Venus. Being close to the Sun allows for observations of solar surface features and their connection to the heliosphere for much longer periods than from near-Earth vantage points. The view of the solar poles will help to understand how dynamo processes generate the Sun magnetic field.

The science payload of Solar Orbiter comprises both remote-sensing and in situ instruments. The in situ instruments will operate continuously. During each orbit, the complete instrument suite will be operated around closest approach, and at the minimum and maximum heliographic latitudes – the segments of the orbit where Solar Orbiter will be farthest below and above the solar equator. Since the orbital characteristics will change in the course of the mission, individual orbits will be dedicated to specific science questions. The RPW (Radio and Plasma Waves) experiment is unique amongst the Solar Orbiter instruments as it will perform both in situ and remote-sensing measurements. RPW will measure magnetic and electric fields at high time resolution using a number of sensors/antennas to determine the characteristics of electromagnetic and electrostatic waves in the solar wind. This instrument includes antennas provided by Stellar Scientific (USA) for which specific alloys are used in order to fulfill the extreme requirements.

Elgiloy – a cobalt chromium-nickel alloy provided by Elgiloy Specialty Metals (USA) – will be used for the spring of the stacer of the antennas (Fig. 1). The flight temperatures for this material are expected to be in between −200 °C and 550 °C (73 and 823 K).

Abraded annealed niobium provided by Goodfellow (USA) or as-received niobium provided by Admat Inc. (USA) are selected to be used on the shield of the antennas (Fig. 1). This material will be exposed to very high solar flux through the mission with a maximum at the perihelion of the orbit of 17.5 kW/m^2. Niobium has been selected because it can withstand high temperature and is

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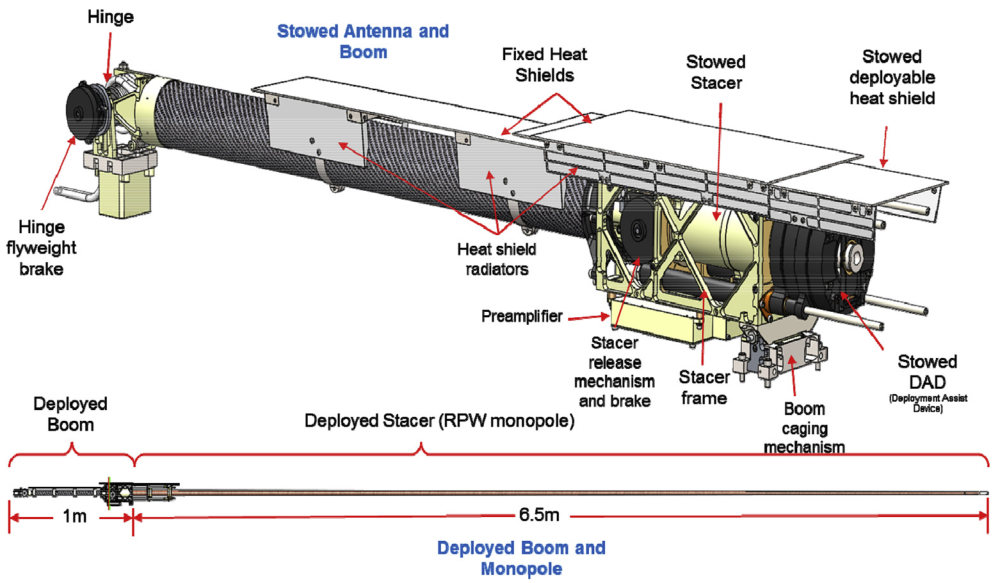

Fig. 1. Scheme of the RPW antenna system relying on two main mechanisms: a rigid, hinged deployable "stub" boom, and a second deployable boom on the end of the rigid boom that forms the monopole receiver. A heat shield deploys and covers the areas of the stub boom and monopole release mechanism that are exposed to full solar illumination during the mission.

compliant with scientific needs (electrical conductivity and photoemissivity). However, this metal has low thermo-optical properties and then a variation of these properties could lead to an important change in the temperature reached due to high solar flux. Abraded niobium was also selected to decrease the solar absorptivity to the total hemispherical emissivity ratio α/ε and then the temperature. The flight temperatures for this material are expected to be in between −160 °C and 700 °C (113 and 973 K).

The knowledge of their thermo-optical properties according to temperature is crucial in order to perform precise thermal analyses and to obtain more accurate temperature predictions. Indeed, the temperature reached on the shield and the antenna during flight has an impact on the elements behind the shield. In this way, measurements of thermo-optical properties were carried out at PROMES-CNRS laboratory at room temperature and up to around 1500 K in high vacuum for these materials in order to cover safety margins.

2. Literature study

For Elgiloy, no data can be found in the literature and only few data are available for niobium. Many of the data for emissivity are normal spectral values and few authors have given data for the total hemispherical emissivity of niobium.

Normal spectral (at 0.63, 0.65, 0.75 and 0.90 μm) emissivity for niobium in high vacuum were obtained at 1000 and/or 1300 K by Wall et al. [1] reporting data from Abbott et al. [2], Maglic et al. [3], Matsumoto et al. [4] and Yi et al. [5]. Some differences can be found in the data, as for example, the normal spectral (0.63 or 0.65 μm) emissivity of niobium varies from 0.42 to 0.35 at 1300 K [1,2,5] and is equal to 0.36 at 2000 K then stays stable up to 2600 K [4]. For other closer wavelengths, the normal spectral emissivity at 1000 K and 1300 K is respectively equal to 0.33 and 0.32 for 0.75 μm and to 0.31 and 0.30 for 0.90 μm [5].

The total hemispherical emissivity for niobium was determined using several techniques but mainly calorimetric ones and more important discrepancies can be found among the data of Maglic et al. [3], Matsumoto et al. [4], Cheng et al. [6] and Howl and Davis [7]. At 1300 K, the values are equal to 0.19 [3] and 0.25 [7]. Cheng et al. [6] give values at lower temperature (0.12 at 1000 K) and Matsumoto et al. [4] at higher temperature (0.22 at 2000 K). These differences can be attributed to different surface roughness, or slight oxidation or contamination of the surfaces as few information are given on the surface state in these works. This point is clearly shown in the interesting review presented by Matsumoto et al. [4] with large data scatter up to 50%.

In order to obtain reliable and useful data for the Solar Orbiter mission, emissivity measurements were carried out on Elgiloy and on two different niobium samples.

3. Experimental set-up and method for emissivity measurement at high temperature

The direct method developed at PROMES-CNRS for the evaluation of the emissivity is based on the measurement of the directional radiance of the material in a given wavelength range and of the true temperature [8–12]. The directional emissivity is defined as the ratio of the directional radiance of the material L′ in a given wavelength range (0.6–2.8 or 0.6–40 μm) to the radiance of the blackbody L° at the same temperature T. Equations (1) and (2) give the expression of both emissivities determined in this work:

$$\varepsilon'_{0.6\text{-}2.8} = L'_{0.6\text{-}2.8}\,(T)/L^{\circ}_{0.6\text{-}2.8}\,(T) \quad (1)$$

$$\varepsilon'_{0.6\text{-}40} = L'_{0.6\text{-}40}\,(T)/L^{\circ}_{0.6\text{-}40}\,(T) \quad (2)$$

with in subscripts the wavelength range (expressed in μm).

The directional radiance measurements are made in the two wavelength ranges for different incidence angles by 10° step (from 0° to 80°, plus 45° and 75°), 0° being normal incidence. The hemispherical corresponding emissivities $\varepsilon^{\Omega}_{0.6\text{-}2.8}$ and $\varepsilon^{\Omega}_{0.6\text{-}40}$ are then calculated by integration of the directional values. The ratio of the large wavelength band hemispherical emissivity ($\varepsilon^{\Omega}_{0.6\text{-}2.8}$) to the total hemispherical emissivity ($\varepsilon^{\Omega}_{0.6\text{-}40}$) allows approaching the α/ε ratio of the solar absorptivity α (0.2–2.7 μm) to the total hemispherical emissivity that governs the thermal equilibrium of materials in a solar environment.

Measurements are performed in high vacuum (10^{-4} Pa) in the

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