Study of H-recombination in Aluminium foils: first irradiation tests with low-energy protons (5 keV) at the DLR Complex Irradiation Facility (CIF).

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ABSTRACT

The current DLR project GOSSAMER aims at establishing solar sails as a powerful and reliable propulsion technique for future space missions. The solar sail propulsion technique basically uses the transfer of momentum from solar photons to a large foil which has been deployed in space and is connected with a payload. The latest design of the GOSSAMER solar sail will use a thin polyimide foil covered on both sides with a 100 nm layer of Aluminium. However, the aging of the foil in a space environment, especially changes in the specular reflectance of the surface, has to be studied very carefully to ensure a proper performance of a solar sail spacecraft over long mission periods. One possible degradation effect is presented: the blistering of the Aluminium surface under proton irradiation. Protons that were stopped in a metal can recombine with free electrons to H-atoms and can finally form bubbles of H_2 within in the material. It depends on several parameters whether this recombination leads to the formation of blisters at the surface of the metal: the energy of the protons, the proton dose, the thermal conditions, the solubility of hydrogen in the metal, impurities, and defects in the material. Previous published laboratory studies showed that blisters on Aluminium surfaces occur at relatively low proton energies (< 100 keV) and high dosages (10^{16} to 10^{18} protons/cm²).

Introduction:

The motivation of this study is to check the possibility of formation of molecular hydrogen bubbles at the surface of Al foil that are exposed to high fluxes of low energy protons. Then H_2-bubbles may cause a blistering that significantly reduces the reflectivity of metallic surfaces, thereby also decreasing the efficiency of future solar sail propulsion technology. Up to now there are no sample returns of metallic surfaces that have been exposed to space conditions and that are not damaged by ATOX. Therefore, laboratory studies are necessary.

What are the H2-blisters and under which physical conditions one can expect the phenomenon?

- H2-blisters are metal bubbles filled with hydrogen molecular gas resulting from recombination processes in metal lattice,
- Blisters are formed in Aluminium at temperatures up to 630 K [Milcius D. et al. 2005]. At higher temperatures the effusion of the hydrogen gas is so large that the gas comes out from the lattice and no blisters can be formed.
- The considered Al foils have to be irradiated by a flux of H or H_2 ions. There is a critical dose of ions above which one can expect the blister formation. The doses and energies are, respectively: 10^{16} p^+ cm^{-2}, 50—70 keV [Milacek L.H. et al. 1967] and 10^{18} H_2 ions cm^{-2}, 1 keV [Milcius D. et al 2005].

Three main recombination processes of protons into Hydrogen:

When an incident proton strikes the target, it penetrates the material. One can distinguish three processes of capturing an electron (Auger, resonant and OBK), and two (Auger and resonant) of losing an electron. The probability of recombination increases with decreasing kinetic energy of the incident protons [Echenique P.M. et al. 1986]. At rest all of the incident protons recombine into Hydrogen. For 5 keV protons the Auger process is the most probable scenario of recombination of protons into Hydrogen.

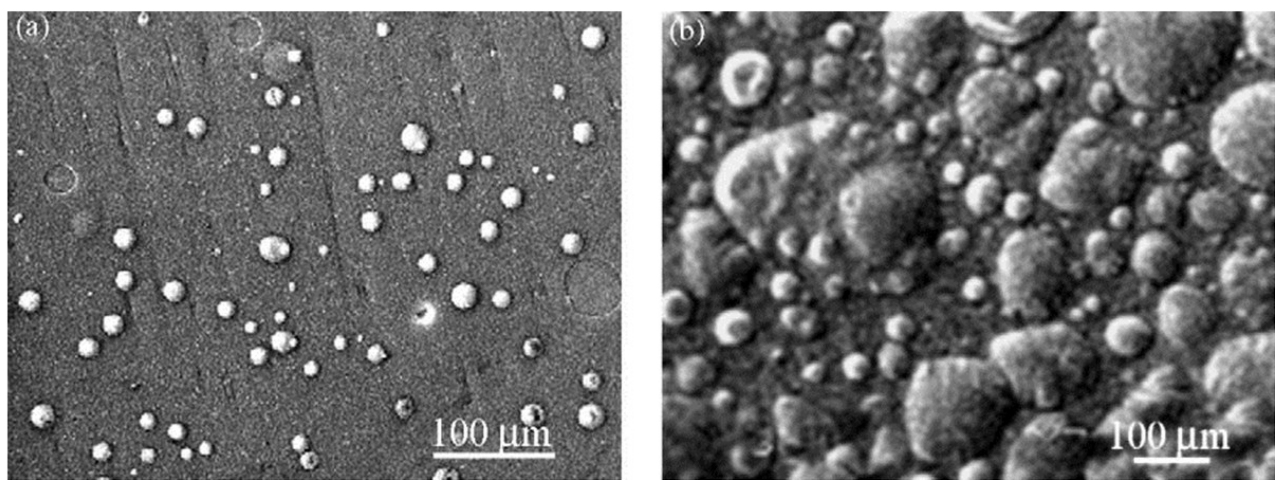
- Auger process: an electron is captured (or lost) by the incident ion to (or from) a bound state assisted by a third body an electron-hole pair [Echenique P.M. et al. 1990],
- Resonant process: the incident ion is neutralized by an electron which is tunneled to the metastable state [Hagstrum H.D. 1954],
- OBK (Oppenheimer-Brikmann-Kramers) process: is a capture process, where an inner or outer shell electron of a target atom is transferred to the moving ion [Sols F. et al. 1988].

Short scenario of blister formation:

- Presence of Hydrogen in the metal lattice causes:
  - Strain in metal lattice [Metzger H., et al 1976, Tomas G.J. Et al. 1983],
  - H atoms change the electronic structure of near neighbor metal atoms [Troiano A.R. Et al. 1960],
- Implantation changes the energy of the system, the energy may be decreased by the aggregation of the H atoms into H clusters [Fujita F.E. Et al. 1976],
- When the H content in the metal exceeds the limit of its solubility, H atoms are rejected from the metal and agglomerate to form bubbles [Milcius D. et al. 2005].

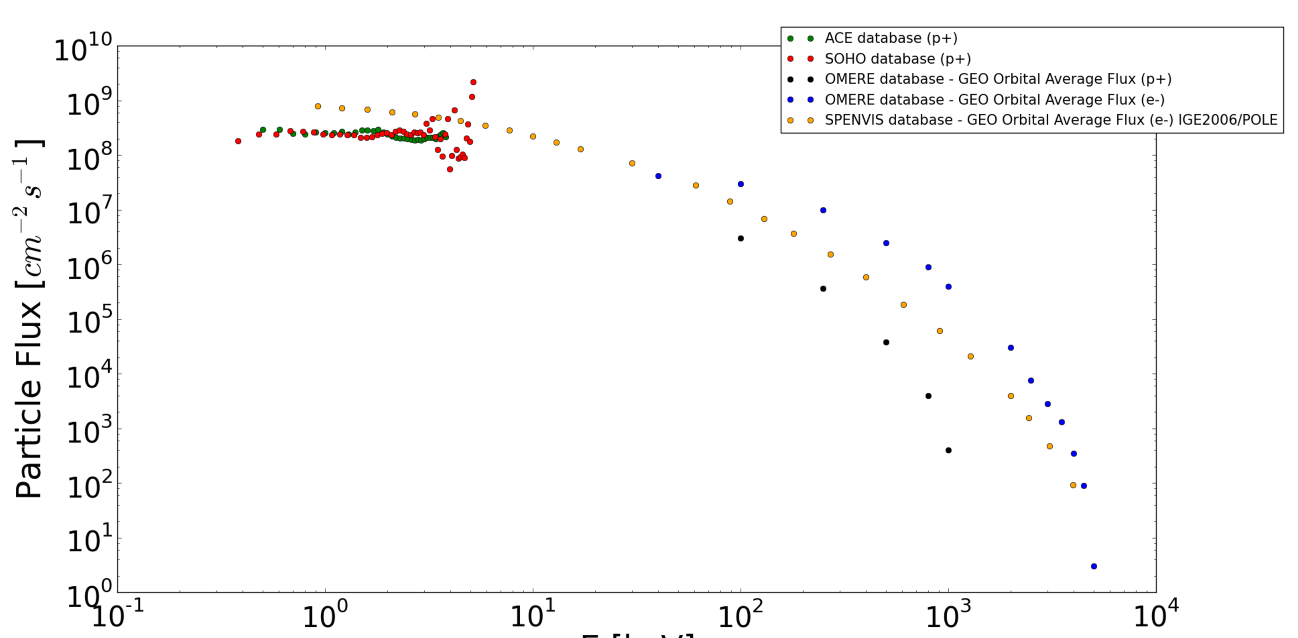
An example of blister formation: Aluminium irradiated by 1 keV H_2 ions:

- The foil was kept in the constant temperature of 320 K during the experiment. The total dose was 10^{18} H_2 ions cm^{-2} [Milcius D. et al. 2005],
- The left picture shows the area of the foil at the end of experiment, right hand side picture shows the same piece of the foil but in the temperature of 450 K. The size of the bubbles is bigger with larger temperatures [Milcius D. et al. 2005].



The Space environment—test of the dose and energy of proton requirement of H2-blisters formation.

- By use of the data from the proton monitor of the SOHO and ACE spacecraft, SPENVIS database and OMERE software it is possible to estimate the flux of Solar protons and electrons at the distance of 1AU from the Sun. The integrated flux over the energy (from 0.29 keV to 5 keV) for the SOHO database is 1.29 x 10^{10} H^+ cm^{-2} s^{-1}, while for the ACE database (from 0.5 keV to 3.84 keV) it is 0.8 x 10^{10} H^+ cm^{-2} s^{-1}. Fluxes are shown in the plot below.



- To reach the critical dose of protons (10^{16} p^+ cm^{-2}) at which H2-blisters creation occurs one has to keep the sample in space for about **70 days**. The flux is taken for 5 keV protons (1.68x10^9 H^+ cm^{-2} s^{-1}).

$$f_{5keV\ p+} \times 70_{days} = \mathbf{1.0x10^{16}}\ H^+\ cm^{-2}$$

Conclusion

At 1AU distance orbits there are a sufficient number of low energetic protons to form H2-blisters.

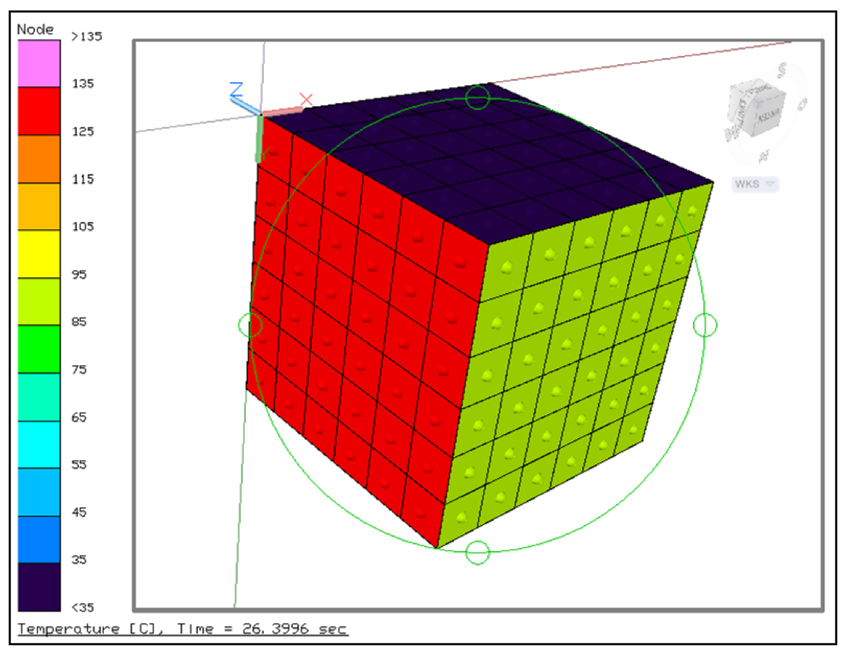
A small cubic model—the test of the temperature requirement of H2-blisters formation

Since at 1AU there is a sufficient number of low energy solar protons to form H2-blisters, one can consider 1 [m] cube size satellite located at 1AU distance orbit from the Sun. The idea is to estimate the temperature of the satellite when the rotation axis is perpendicular to the orbit's plane. The cube is made with 10 [µm] polished Aluminium plates. The relation between angular velocity of the cube and temperature of walls is presented.

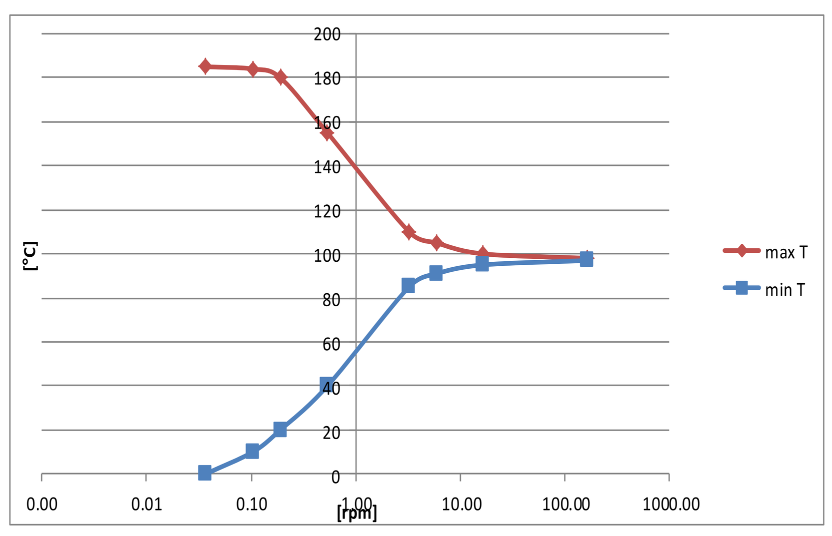
Model Parameters:

Edge length	**1 m**
Material (Alloy)	**Aluminium (7075 T6)**
Distance to the Sun	**1 AU**
Density	**2810 kg m^{-3}**
Heat Conductivity	**130 W m^{-1} K^{-1}**
Heat Capacity	**960 J kg^{-1} K^{-1}**
Surface	**polished**
Solar Absorptivity	**0.15**
IR Emissivity	**0.05**

- The right picture shows the concept of the shell cube made with 10 [µm] polished Aluminium plates. The cube is rotating with a frequency of 1 rpm. The temperature of the wall exposed directly to the sun is 135°C, while top and bottom walls have temperatures of 20°C.



- The plot below shows a relation between the temperatures of the cube walls: exposed (red line) and in the shade side (blue line) to the Sun as a function of rotation speed of the box.
- For small rotational velocities the box-satellite's walls have got more time to absorb energy (red line). Also for small rotational velocities the walls which are not exposed to the sun have more time to cool down by radiation. Above 100 rpm the walls have small amount of time to irradiate the heat, the temperature becomes uniform.



Conclusion

The critical value of the temperature above which H2-blisters formation is impossible is approx. 630 [K] [Milcius D. et al. 2005]. From the test model the maximum temperature of the cubic satellite exposed to the Sun is approx. 460 [K]. The temperature is sufficiently low to fulfill the temperature requirement for blister formation.

The plan of the irradiation test by use of the Complex Irradiation Facility at DLR (Bremen).

To check the possibility of H2-blister formation, one has to ensure in laboratory the conditions which are present in space. The Complex Irradiation Facility at DLR (Bremen) is designed to fulfill such requirements. It possess protons and electron accelerator, sun simulator, deuterium and Vacuum-UV source as well.

The plan of the test is as follows. The Al-foil will be kept in high vacuum conditions (10^{-9} mbar) with constant temperature of 300 [K]. The probe will be irradiated by low energy protons (5 keV) for over 8h. According to the SRIM software, the projected stopping range of the 5 keV is 70.2 nm. The total dose of protons will be 2x10^{17} cm^{-2}. Then the irradiated sample will be checked ex-situ with optical and electron microscope whether H2-blisters are formed.

Conclusions

The formation of H2-bubbles is up to now a hypothetical process which may take place in space. The presented requirements for total dose of protons as well as temperatures clearly show that the occurrence of the phenomenon is highly probable. Since no metallic samples returned to Earth beyond ATOX influence it is highly important to check the possibility of blister formation in the laboratory. The Complex Irradiation Facility at DLR, Bremen is an ultimate device to make this judgment.

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DLR Deutsches Zentrum für Luft- und Raumfahrt
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