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Degradation of metallic surfaces under space conditions, with particular emphasis on Hydrogen recombination processes

Maciej Sznajder [a,*], Ulrich Geppert [b,c], Mirosław Dudek [d]

[a] DLR Institute for Space Systems, University of Bremen, Robert Hooke Str. 7, 28359 Bremen, Germany
[b] DLR Institute for Space Systems, System Conditioning, Robert Hooke Str. 7, 28359 Bremen, Germany
[c] Kepler Institute of Astronomy, University of Zielona Góra, Lubuska 2, 65-265 Zielona Góra, Poland
[d] Institute of Physics, University of Zielona Góra, Szafrana 4a, 65-069 Zielona Góra, Poland

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Abstract

The widespread use of metallic structures in space technology brings risk of degradation which occurs under space conditions. New types of materials dedicated for space applications, that have been developed in the last decade, are in majority not well tested for different space mission scenarios. Very little is known how material degradation may affect the stability and functionality of space vehicles and devices during long term space missions.

Our aim is to predict how the solar wind and electromagnetic radiation degrade metallic structures. Therefore both experimental and theoretical studies of material degradation under space conditions have been performed. The studies are accomplished at German Aerospace Center (DLR) in Bremen (Germany) and University of Zielona Góra (Poland).

The paper presents the results of the theoretical part of those studies. It is proposed that metal bubbles filled with Hydrogen molecular gas, resulting from recombination of the metal free electrons and the solar protons, are formed on the irradiated surfaces. A thermodynamic model of bubble formation has been developed. We study the creation process of H_2-bubbles as function of, inter alia, the metal temperature, proton dose and energy. Our model has been verified by irradiation experiments completed at the DLR facility in Bremen.

Consequences of the bubble formation are changes of the physical and thermo-optical properties of such degraded metals. We show that a high surface density of bubbles (up to 10^8 cm^{-2}) with a typical bubble diameter of ~0.4 μm will cause a significant increase of the metallic surface roughness. This may have serious consequences to any space mission.

Changes in the thermo-optical properties of metallic foils are especially important for the solar sail propulsion technology because its efficiency depends on the effective momentum transfer from the solar photons onto the sail structure. This transfer is proportional to the reflectivity of a sail. Therefore, the propulsion abilities of sail material will be affected by the growing population of the molecular Hydrogen bubbles on metallic foil surfaces.

Keywords: Space environmental effects; Recombination; Hydrogen embrittlement; Blistering

1. Introduction

Metallic structures are commonly used in space technology. They build skeletons of spacecrafts, they protect satellites' interiors from rapid temperature changes (MLI blankets), or they are used as highly reflecting mirrors of optical space telescopes. Nowadays, metals are also used as thin layers on polyimide-type foils which have a broad usage in the solar sail technology.

A failure of a space mission may be the result of a change of metallic structure properties caused by the

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* Corresponding author.
E-mail address: Maciej.Sznajder@dlr.de (M. Sznajder).

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Nomenclature

α	model parameters which determines gradient of bubble growth
α_S	solar absorptance
α_C	parameter of Lifshitz–Slyozov–Wagner theory
A	area of the sample
A_b	area of the sample covered by the bubbles
A_t, A_t^*	transition amplitude, complex conjugate of transition amplitude
b	impact factor
BS	backscatter coefficient
d_{PR}	projected range
D_H	diffusion coefficient for H atoms in a given material
$\Delta(t)$	difference of concentration of Hydrogen atoms at the bubble boundary and C_∞
C_∞	concentration of Hydrogen atoms far beyond the bubble
E	energy of incident ion
E_{int}	internal energy of molecules/atoms located at certain positions in the metal lattice
E_Y	Young module
E_{min}	ion's lowest energy recorded by the SOHO/ACE detector system
E_C	critical energy of incident ions above which ions pass through the material
$F_{gas,i}$	free energy of gas inside the ith bubble
F_H	free energy of H atoms located outside bubbles in the metal lattice
F_{H_2}	free energy of H_2 molecules located outside bubbles in the metal lattice
$F_{md,i}$	free energy of metal deformation caused by expanding ith bubble
$F_{surf,i}$	surface free energy of the ith bubble cap
F_{config}	free energy of a sample covered by bubbles
γ	Poisson coefficient
G_i	fraction of H_2 molecules merged into the ith bubble
H_i	sum of partial derivatives
$H_{Sun}(d)$	radiation energy received from the Sun per unit area for a given distance d
η_{max}	relation between the number of H_2 molecules and the H atoms in the metal lattice
ϵ_H	migration energy of the H atom in the metal lattice
ϵ_{H_2}	binding energy of the H_2 molecule to a vacancy
ϵ_{cell}	size of a grid cell that covers the irradiated sample
ϵ_t	normal emittance
I	proton flux
I_E	integrated proton flux
I_d	flux of protons at distance d from the Sun
k_B	Boltzmann constant
M_u	molar mass of the sample's material
N	number of time steps up to a given state of bubble growth
N_0	number of lattice sites
N_B^T	total number of bubbles at the irradiated sample
N_{cell}	number of cells
N_H^T	total number of H atoms in the sample
$N_{H_2}^T$	total number of H_2 molecules in the sample
$N_{H_2,i,j}$	number of H_2 molecules add to the ith bubble in the jth time step
$N_{H_2}^{out.bubbles}$	number of H_2 molecules located in the lattice but outside bubbles
$N_{H,j}$	number of recombined H atoms in the jth time step
$N_{diff,j}$	number of H atoms which diffuse from the sample out in the jth time step
Ω	number of ways in which the H_2 molecules can be arranged on the lattice sites
$Q, Q\prime$	eigenstate of the incident ion and an electron before (Q) and after ($Q\prime$) recombination event
P	probability of a recombination event
p_i	pressure of the gas inside the ith bubble
q	momentum
Δq_i	momentum transfer of a photon to the ith cell of the degraded foil
$\Delta q_{max,i}$	momentum transfer of a photon to the ith cell of a perfect mirror
SC	solar constant
d	distance from the Sun
r_i	radius of the ith bubble
$\bar{r}$	average bubble radius
$r_{i,0}$	initial radius of the bubble
$r_{max,i}$	maximum radius of the i^{th} bubble
ΔR	decrease of the specular reflectivity
S	entropy
σ	surface tension
σ_{SB}	Stefan–Boltzmann constant
Σ_A	cross section for Auger recombination process
Σ_R	cross section for resonant recombination process
Σ_{OBK}	cross section for Oppenheimer–Brinkman–Kramers recombination process
Σ_{total}	total cross section for recombination processes
Δt_j	time step
T	temperature
t_s	number of days in space until a probe will collect a given dose of protons