ESAIL D22.1
Tether coating report

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Prepared by: University of Helsinki, Timo Rauhala
University of Helsinki, Göran Maconi
University of Jyväskylä, Taneli Kalvas

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Approved by: University of Helsinki, prof. Edward Hæggström

(List of participants:)

Participant no.	Participant organisation	Abbrev.	Country
2	University of Helsinki	UH	Finland

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1. Purpose

The purpose of this document is to report on testing of wire coatings to minimize the potential of cold weldings induced by spacecraft launch vibration and to determine the increase in thermal emissivity provided by the coating. The coating also serves as a possible way to increase the tether's optical visibility to onboard cameras.

2. Introduction

The Electric Solar Wind Sail (E-sail) uses centrifugally stretched positively charged tethers to create thrust from the momentum flux of the solar wind. A full-scale E-sail should produce one newton of thrust from one hundred 20 km long tethers. Other configurations featuring 2000 km total tether length are also possible.

For micrometeoroid resistance, multifilament tethers are needed. In addition, the tethers must be electrically conductive, thin and strong enough to sustain the centrifugal force generated by the rotating E-sail.

The electric conductivity, density, and tensile strength of the Al(Si1%) bonding wire meet the requirements of the E-sail tethers. Al-Al bonds are known to be reliable in long term use.

The tethers can be coated as a protection against cold welding between the tether wires due to booster rocket launch vibrations. Importantly, coating the tethers may also increase their thermal infrared emissivity in space. Pure aluminium has poor emissivity $\varepsilon = 0.02 - 0.03$ [1]. To enable E-sail missions inside Earth's orbit, it is necessary to increase the tether's thermal infrared emissivity. The choice of coating material is important as it defines the equilibrium temperature of the tether for a given solar distance and - angle. The tether should remain cold, because heating reduces the mechanical properties of aluminium (tensile strength, electrical conductivity).
The coating may also increase the diffuse reflectance of the tether and therefore its optical visibility to onboard cameras, although this is of secondary importance.

3. Tether coating

In an initial inquiry into various coating options four methods were tested. Boron nitride (hBN) and tungsten disulfide (WS_2) sprays, water vapour oxidation, and Atomic Layer Deposition (ALD) based oxidation, Figs 1, 2.

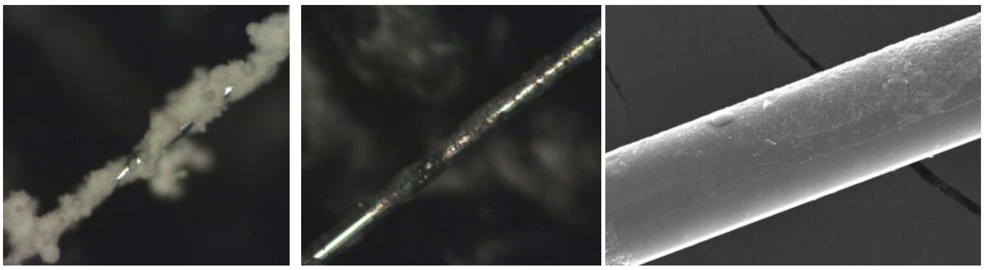

Fig 1. Various coating methods. (left to right) hBN,WS_2, and H_2O vapor. The two sprays were applied from a distance of 20 cm for 2 sec. Water vapor was applied for varying times, 30 min pictured.

ALD was chosen as the preferred coating method because it can produce surfaces with even 0.1Å precision in thickness, Fig 2, and because it can be employed post tether fabrication. All the other tested methods produced an irregular surface and were therefore rejected. ALD is a thin film deposition technique based on sequential use of a gas phase chemical process.

The test samples (wires, tether) were coated by a 100 nm thick layer of aluminium oxide in an ALD reactor run by the Laboratory of Inorganic Chemistry of the University of Helsinki.
Aluminium oxide was chosen because of the relative ease of ALD deposition as well as since it is the same material as the natural oxide layer on the wires (this eliminates a need to clean the wire before coating). The emissivity ε of heavily oxidized aluminium is 0.2 – 0.3 [1] whereas that of pure aluminium oxide is 0.26 – 0.42 [2].

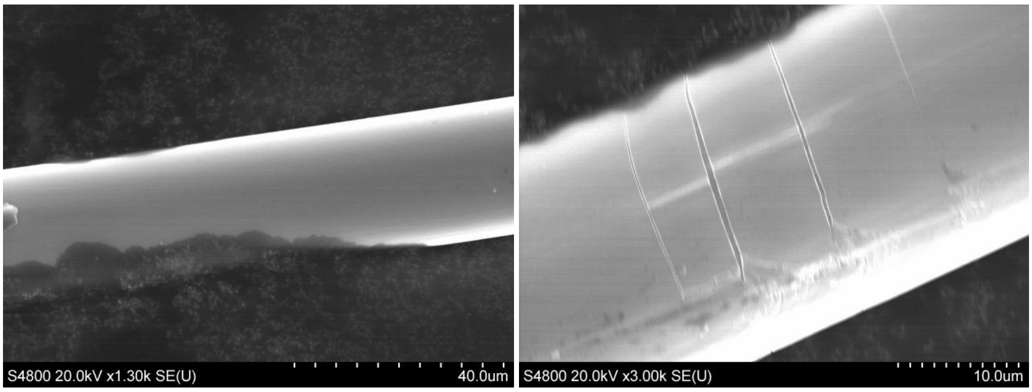

Fig 2. SEM pictures of ALD coated wires. The surface is uniform but when bent, cracks appear on the coating.

3.1 Protection against cold welding

Cold welding is a solid-state welding process in which two clean, flat surfaces of a similar metal strongly adhere (covalently) when brought to contact under vacuum-like conditions.
The capability of the coating to resist cold welding was experimentally tested by trying to bond the coated wires ultrasonically, thus simulating (exaggerating) the vibrations present during spacecraft launch.

3.1.1 Simulating launch vibrations

Two Tanaka AL-2 spools, containing dia=50 µm Al(1%Si) wire and two-wire-heytether comprising dia=50 µm and dia=25 µm Al(1%Si) wires, were coated with Al_2O_3. The coating thickness was monitored during the ALD process and the process was stopped when the target thickness 100nm was reached.

The ultrasonic bond development exhibits four phases [3], pre-deformation phase, cleaning phase, contact development phase, and completed bond phase. For this report the *cleaning phase* is most critical, as during it the natural (or artificially added) oxide layer on the bonding wire is removed to allow adhesion between clean metal surfaces.

The test aims to prove that a thicker Al_2O_3 layer results in a prolonged cleaning phase during bonding. Since the bond time in the test is fixed (as is the duration of the launch), a longer cleaning phase results in a weaker bond or a failure to bond.
The test bonds were made on gold coated carbon fiber substrates manufactured by Cicorel. The substrate is designed to be used to test bonding machines, bond parameters and -wires. The exact material of the pad is relevant only after the cleaning phase, so for our purpose of simulating the spacecraft launch vibrations, a gold pad is acceptable. In the real case all wire surfaces would be coated, so the protection provided by the coating against cold welding is doubled (the coating has to be broken on two wire surfaces for cold welding to occur).
The bonds were created using a K&S 4123 (60 kHz) bonder and a standard 50 µm DeWeyl wedge. All together 83 bonds were tested, see Table 1. The results suggest that the coating reduces the probability of cold welding in a situation resembling the launch.

Table I	Attached bonds	
Bonding parameters	Uncoated	Coated
UST 20, USP 0.70, BF 170	50%	0%
UST 20, USP 0.70, BF 185	50%	0%
UST 20, USP 0.70, BF 200	100%	0%
UST 20, USP 0.70, BF 215	100%	0%
UST 20, USP 0.70, BF 230	100%	0%
UST 30, USP 1.15, BF 280	100%	11%

UST = Ultrasonic time (ms), USP = Ultrasonic power (W), BF = Bond force (mN).

3.1.2 Evaluation of the usability of ALD

A drawback of the ALD method is that since the tether is coated after being reeled onto the output spool, parallel wires that touch each other may become adhered together by the coating.
To measure the strength of this kind of adhesion, the coated tether was subjected to two different unreeling tests. Test#1: the force required to pull the tether out of its spool was measured, and Test#2: the tether was unreeled by gravity, Fig 3.
In Test#1, 10 cm of tether was unreeled from the spool ten times at 0,5 cm / sec. The extraction force was measured by a Futek LSB200 load cell, Fig 4. The result of this test was verified using the other setup, where the weight required to successfully unreel the tether was determined to be 1,1 – 1,4g.

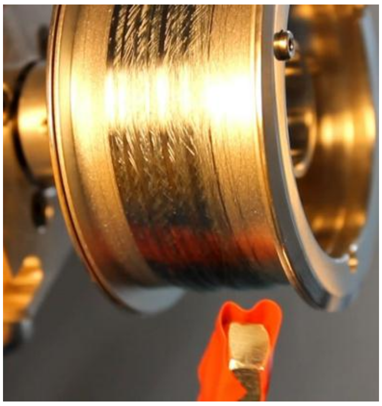

Fig 3. Unreeling coated tether. A weight is attached to the tether and the spool is turned by a motor.

The adhesion of the tether to the underlying tether structure is dominated by the adhesion of the base wires to each other whereas the adhesion of the loops to the structure is weaker. This is likely due to the larger surface area of the base wire as well as to the tension applied to the base wire during the manufacturing process.

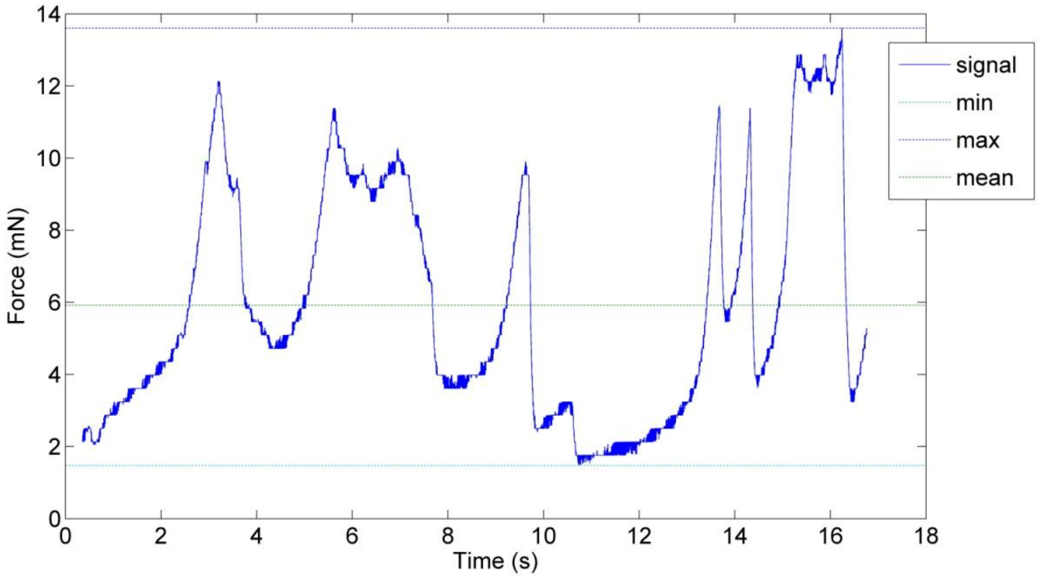

Fig 4. Typical output from the load cell used to measure the force required to unreel tether from the spool. The strength of the adhesion between the coated wires varies as it is unspooled.

3.2 Emissivity measurements

One of the most important things impacting the life-time or durability of the tether is its equilibrium temperature. The temperature affects the material properties of the aluminium wire under tension, for example creep and the wires tensile strength. The equilibrium temperature, T_e, of the tether in space depends highly on the emissivity of the tether as radiation is the only heat loss mechanism for such a long and thin structure.

The equilibrium temperature, T_e, of a single 50 μm aluminium wire was calculated using a zero-dimensional computer simulation as a function of the distance from the sun and the emissivity of the wire. The calculation assumed (1) 1.4 kW/m^2 $(r_0/r)^2$ photon flux from the sun (r_0 is 1 AU) perpendicular to the wire, (2) 1 mA current flowing in the wire causing resistive heating, (3) a heat flux from the solar wind electrons impacting the wire at 20 keV energy (1 mA for 20 km distance), and (4) radiative heat exchange with the background space at 4 K. The radiative components are affected by the thermal emissivity constant, ε. Literature values for ε are 0.03 for polished and clean aluminium [1] and >0.2 for bulk Al_2O_3 [2]. These emissivity values seem to be sufficient according to the thermodynamic simulation (the melting point of aluminium is 933 K), but unfortunately the use of bulk data to such small structures as the tethers and the nanometre scale coating is somewhat dubious.

According to Wien's displacement law the most intensive photon wavelength for radiation emitted by a body at 600 K is 4.8 μm, and the aluminium oxide thickness is at least one order of magnitude smaller that the wavelength. Consequently, the emissivity of the bulk aluminium oxide is not directly applicable and the the emissivity of the tether wire has to be measured.

3.2.1 Emissivity measurement setup

The basic idea for the emissivity measurement is to heat the wire in vacuum while measuring the voltage drop across the wire to get a resistance value as a function of the wire temperature. The emissivity strongly affects the thermodynamics of the thin wire in which the heat conduction is low compared to the radiated heat. Because of boundary effects, non-constant resistivity of aluminium, power-law dependence of radiation, etc. the only way to obtain the emissivity of the wire is to compare the experimental data to data from a computer simulation.

The emissivity measurements were conducted at the University of Jyväskylä. The measurements were done in a vacuum chamber, Fig 5, at low 10^{-7} mbar pressure. The wire was bonded to 15x10x1 mm^3 aluminium plates (plate A) at each end, which were bolted to larger aluminium plates (plate B) which mechanically connected the wire under measurement to a rigid support frame keeping the wire approximately straight. The B-plate at each end connected the measurement wires coming from vacuum feed-throughs. Outside the vacuum the electronics, Fig 6, were connected to the measurement wires. The electronics use a four-wire connection. Two of the wires were used for the bias current and two for the voltage measurement. Therefore the biggest confounding contribution to the measured resistance came from the contact resistance between plate A and the wire (the bonded contact). The measurement electronics was connected to a computer control/DAQ system, National Instruments PCI-6229, that collected data at 10 kHz sampling rate. The device was calibrated done with 100 ohm 1 % resistor and a Fluke 87 IV multimeter by driving the measurement current through the resistor and measuring the voltage drop with the multimeter. The current setting and voltage reading calibration coefficients were set accordingly.

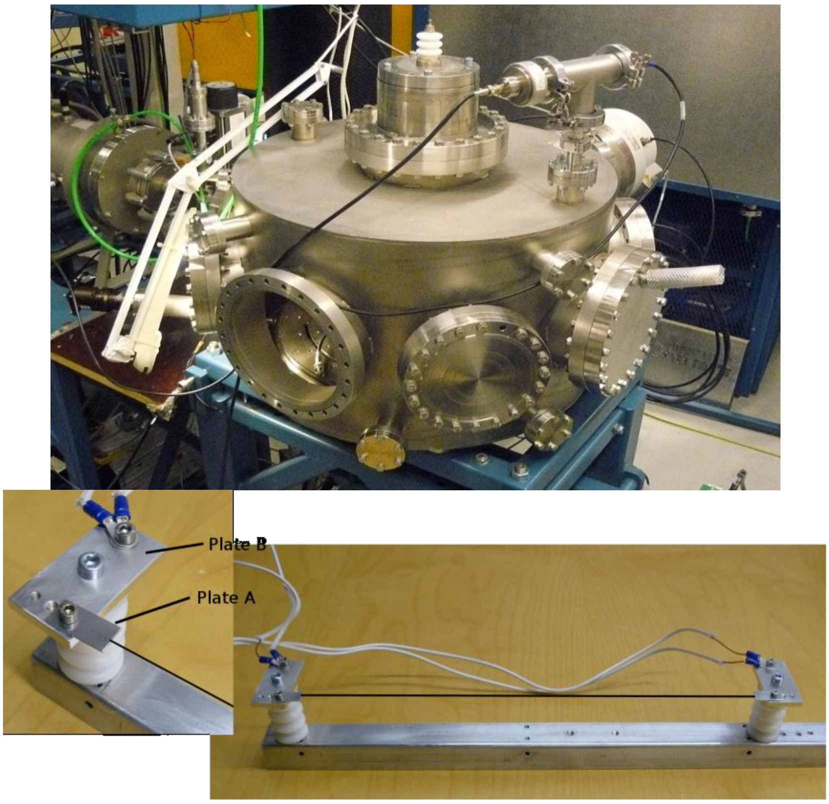

Fig 5. The vacuum chamber used in the measurement (top). Emissivity measurement setup is inside vacuum chamber. The tether wire is bonded to plate A, which is bolted to plate B, where the electrical connections are made. The tether wire thickness is exaggerated in the image (bottom).

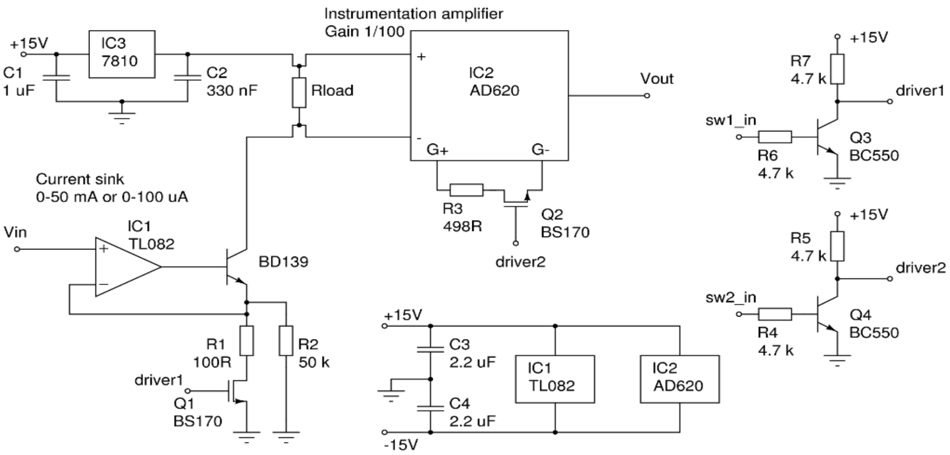

Fig 6. Electronics developed for emissivity measurement. It provides four-wire resistance meter functionality with two ranges for currents and two gain settings.

3.2.2 Simulation program

The simulation program used to model the heated tether wire solves the 1-D heat equation where resistive heating, heat conductance, and radiative losses are taken into account. The simulation discretizes the wire of length L into N (nominal value 100) cylindrical pieces or *nodes* which are assumed to have a temperatures T_i. Each cylinder therefore has a length dx. The systems is iterated with dt time steps from a starting point of fixed T=300 K. At each time step the nodal temperatures are updated according to the local energy flow: $\Delta T = \frac{P dt}{c(T_i)\rho A dx}$, where $c(T)$ is the heat capacity of aluminium as a function of temperature, ρ is the density of aluminium, A is the cross section of the aluminium wire and P is the sum of heat fluxes to the node.

The heat flux calculation is done taking in account the heat conductance $k(T)$ as a function of temperature whereas the emissivity is assumed to be a linear function of temperature $E(T)=E_A+E_B \cdot T$. The ends of the wire are assumed to be in fixed at 300 K (within +/-2 C of the laboratory temperature). The heat flux to the ends is observed and the corresponding temperature rise in plate A is calculated assuming that no heat is conducted away from the system. These temperature increases have been under 0.5 K in all cases.

Data for pure 100 % aluminium was used even though the tether material contains 1 % silicon. This approximation was made since relevant data was not found (as a function of temperature) for the alloy in question.

3.2.3 Measurements and analysis

All emissivity measurements were done using the same measurement sequence, but with different current values. For the 25 μm wire the heating currents were: 1 mA, 5 mA, 10 mA, 15 mA, and 20 mA and the low current for the resistance measurement was 50 μA. For the 50 μm wire the heating currents were: 5 mA, 10 mA, 20 mA, 40 mA, and 60 mA and the low current for resistance measurement was 320 μA. Each measurement consists of (a) 1 sec of background measurement with zero bias, (b) 1 sec of resistance measurement with low current, (c) 200 sec of heating, (d) 200 sec of resistance measurement with low current and (e) 600 sec of cooling with zero current before the next measurement cycle.

The data was fitted by a computer program that minimizes the χ^2 deviation between the simulation and the measurement using a Nelder-Mead nonlinear simplex algorithm. The free parameters in the fit were the wire thickness and the two coefficients E_A and E_B for emissivity. The emissivity was assumed to be a linear function of temperature $E(T)=E_A+E_B \cdot T$. The fitting was done at the static situation when heating is on (time 100-200 s). The wire thickness achieved this way was 24.7 to 25.2 μm for nominally 25 mm thick wires and 48.9 μm to 52.0 μm for nominally 50 μm thick wires. The measured resistances for the 21.12.2011 test are plotted in Fig 7 together with the fitted simulation results. In Fig 8 the temperature profiles of the wire according to the simulations is presented.

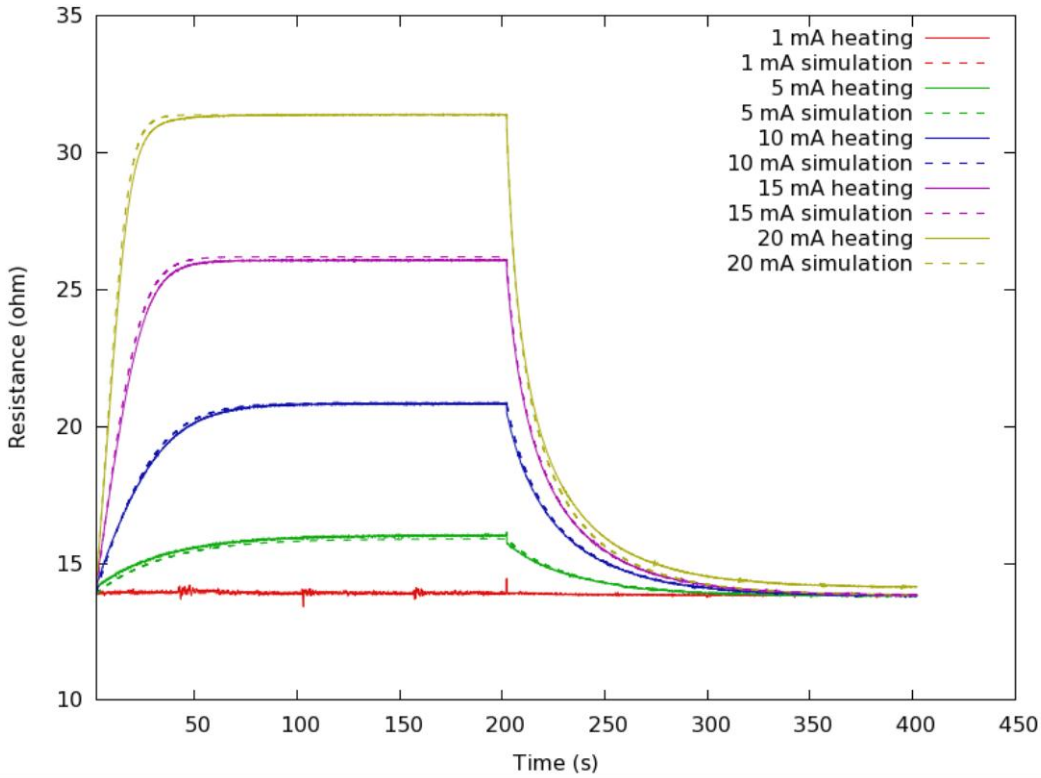

Fig 7. Resistance of the 246 mm long 25 mm in-diameter tether wire in the emissivity measurement sequence for five different heating currents.

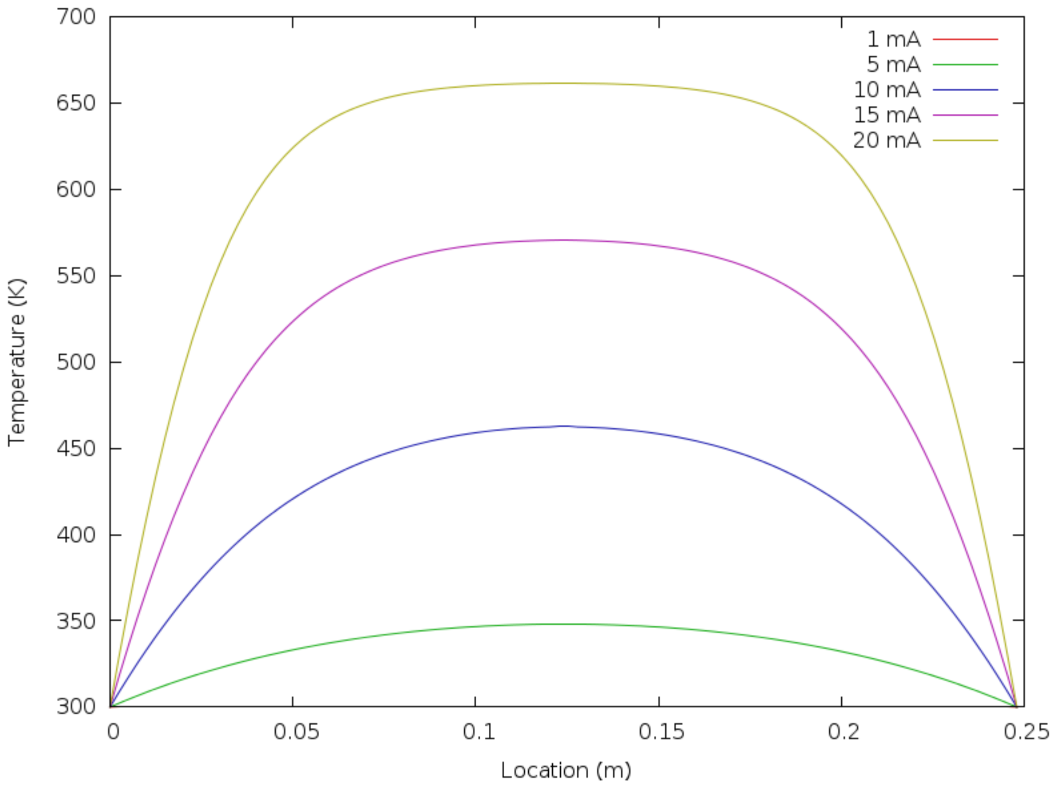

Fig 8. Simulated spatial distribution of temperature on wire at t=200 s, before switching to lower bias current.

All measured emissivities as a function of temperature are plotted in Fig 9 together with data from the Engineering toolbox [1] for unoxidized aluminium. The temperature range in measurements is 300 to 650 K. The plot is extended to 1000 K to include the third Engineering toolbox data point. The emissivity coefficients are also presented in table 2.

Table 2. Fitted emissivity coefficients.

	E_A	E_B
Al_2O_3 50 µm (16.10.2013)	0.0300264	0.0001213
Al_2O_3 50 µm (28.10.2013)	0.0998565	0.0000365
Al_2O_3 25 µm (27.02.2012)	0.0643278	0.0000642
Al_2O_3 25 µm (17.02.2012)	0.0309143	0.0000988
Uncoated, 25 µm (21.12.2011)	0.00280739	0.0001066
Uncoated, 25 µm (07.12.2011)	-0.00354228	0.0001150

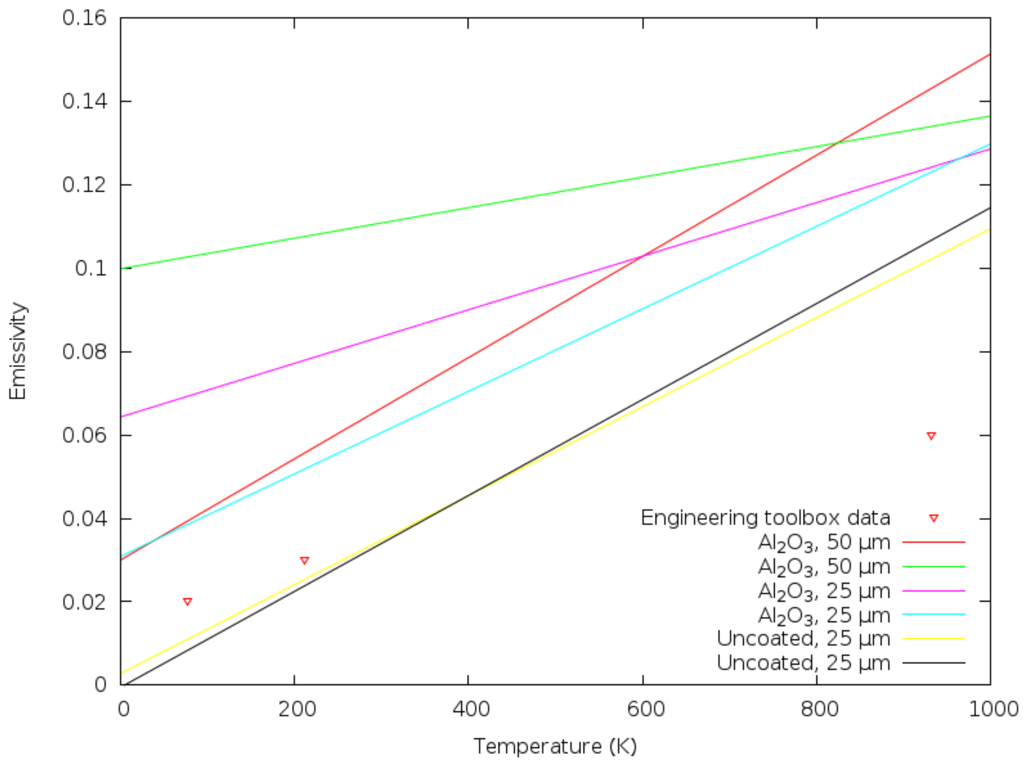

Fig 9. Measured emissivities of tether wire samples together with three data points from the literature.

4. Discussion and conclusions

Four coating methods were tested. ALD-based oxidation was chosen as the preferred coating method for its ability to produce surfaces with well-controlled thickness (even to 0.1Å precision). The other methods provided an irregular surface and were therefore rejected from further investigation.

A launch vibration simulation showed that the coating lessens the probability of cold welding two wires to each other. However, as a result of the ALD treatment post tether production, the wires are partly attached *by the coating.*

Although the bonds on the tether withstand a pull force exceeding 50mN, the minimum safety margin between the extraction force necessary for unreeling the coated tether from the spool and the sustainable pull force of the bonds is relatively low, approximately two thirds of the bonds strength.

This result suggests that a more densely packed spool could lead to problems due to the adhesion caused by the coating. A different approach to coating should therefore be investigated.

In principle it would be possible to integrate the ALD method into the Tether Factory and to coat the tether before it is reeled onto the flight spool. Using this approach avoids the main problem with the ALD method, wires adhering to each other. These kinds of Roll-to-Roll ALD systems exist [4].

The increase in thermal infrared emissivity provided by the 100 nm thick Al_2O_3 coating is rather small; the emissivity is roughly doubled, although the variance of the measurements is significant, as seen in Fig 9. A thicker layer of coating or a different coating material could perhaps be applied to further still increase the emissivity.

This report answers the two main questions of the ESAIL FP7 WP22; the coating lessens the probability of cold welding two wires to each other during spacecraft launch vibrations and the thermal infrared emissivity of the tether is increased by the coating.

References

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[2] Mikron. *Table of emissivity of various surfaces for infrared thermometry*, http://www-eng.lbl.gov/~dw/projects/DW4229_LHC_detector_analysis/calculations/emissivity2.pdf, November 2013

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