Automatic 4-wire Heytether production for the Electric Solar Wind Sail

Timo Rauhala[1,*], Henri Seppänen[1,2], Jukka Ukkonen[1], Sergiy Kiprich[3], Göran Maconi[1], Pekka Janhunen[2] and Edward Hæggström[1]

1 Department of Physics, University of Helsinki, P.o.Box 64, FIN-00014 University of Helsinki, Finland
2 Finnish Meteorological Institute, Helsinki, Finland
3 National Science Center Kharkov Institute of Physics and Technology, Institute of High Energy Physics and Nuclear Physics, Ukraine
***(timo.rauhala@helsinki.fi)**

Abstract We present a method for bonding micrometer-thick metal wires together to produce 4-wire Heytether for the Electric Solar Wind Sail (E-Sail). An E-Sail is composed of one hundred 20 km long Heytethers. The aluminum tether features a base wire to which three interleaving loop wires are ultrasonically bonded. A multiwire tether provides micrometeoroid resistivity. The maximum sustainable pull strength of 99 % of the bonds must exceed 50 mN and no three consecutive bonds may be weaker than this limit value.

We used a custom built tether factory to produce tether from 25 µm and 50 µm wires. To achieve fully automated ultrasonic wire-to-wire bonding, the factory utilizes the ultrasonic signal from a commercial 60 kHz bonder. The factory also features microcontrollers and optical feedback.

The method was validated by producing a 1 km long continuous tether carrying 90.000 bonds. Image and text data of each bond were collected during production. The main production problem was aluminum accruing into the grooves of the bonding wedge. The wedge was manually cleaned seven times during this run. The average production rate was 1.4 m /hour.

Six 15 m long tethers were fabricated in preparation for space tests. One piece was selected to fly with the EstCube-1 satellite in 2013. This mission experimentally determines the strength of the E-Sail effect. Destructive pull tests were carried out on the other five tethers to determine the quality of the fabrication process. The measured average maximum sustainable pull force for unstrained bonds was (100 ± 5) mN.

These results indicate that Heytether production could be automated to a degree where the production of a large-scale E-Sail, featuring 200 million wire-to-wire bonds, is possible.

Keywords: ultrasonic wire bonding, electric solar sail, Heytether

Introduction The E-Sail is a space propulsion invention exploiting the dynamic pressure of the solar wind [1]. It uses centrifugally stretched positively charged conductive tethers to create thrust from the momentum flux of the solar wind. The tethers are kept charged by an onboard electron gun that disposes electrons from the spacecraft at the same rate as the tethers collect them from surrounding plasma. In space the tethers must be micrometeoroid resistant [2]. We use ultrasonic bonding to create an aluminum multiwire Heytether structure (Figs 1 & 3.) to address this issue. A 4-wire structure prolongs the expected lifetime of a 20 km long tether from minutes for a single wire structure to years [3]. An E-Sail composed of one hundred 20 km long tethers produces an estimated 1 N of thrust [4]. A large scale 1 N E-Sail requires over 200 million wire-to-wire bonds, 99% of which must sustain the centrifugal force created by the spin of the system. For a 20 km long tether this is simulated to be 50 mN. Moreover, no three consecutive bonds may be weaker than this limit value. In this paper we introduce an automatic process to produce a tether that satisfies these requirements. We also evaluate the quality of the produced construct.

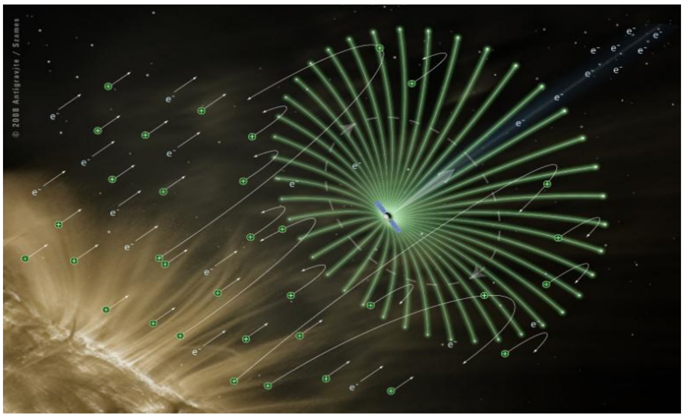
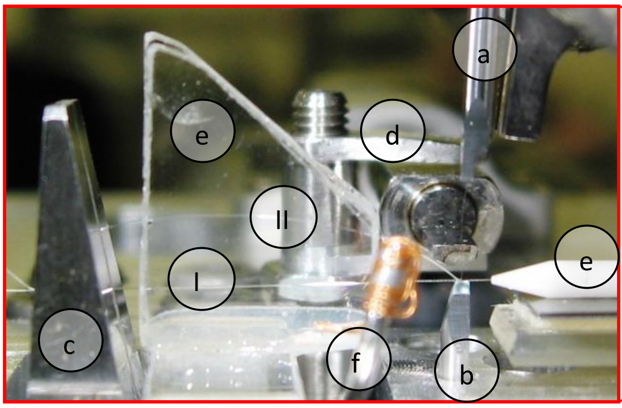


Fig 1. E-Sail concept. Centrifugally stretched multiline tethers are kept positively charged by an onboard electron gun.

Methods Ultrasound bonding is widely used in the electronics industry to attach metal wires to metal plates. However, applying the method to interconnect two or more wires has not been reported before we published on tether production [5]. Continuing these efforts we have automated the tether production cycle and successfully developed a 4-wire production technique.

The Tether Factory [6] (Fig. 2.) is a custom made device, designed to produce Heytether from three 25 μm by diameter AlSi(1%) loop wires and a 50 μm by diameter AlSi(1%) base wire.



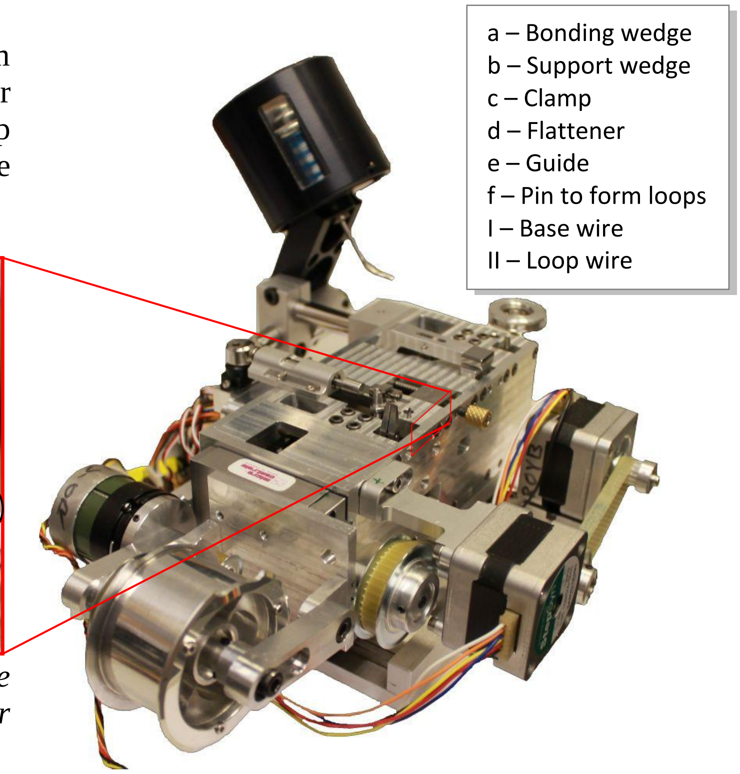


Figure 2. Successful bond (vertical bond wire after wedge retraction. (left), automatic tether factory (right).

To achieve fully automatic production it employs three open source Arduino Mega 2560 microcontrollers, custom built electronics and software. It also employs a camera with dedicated image grabbing software.

The most important challenge in the process is to repeatedly and accurately place and fix the wires for bonding. The allowed lateral deviation in wire placement is (10 ± 2) μm. To achieve this target the clamps, tension arm and wire brake (which reduces vibrations in the wire due to spooling) must be crafted to 20 μm precision.

The Tether Factory holds the base wire firmly in place on a specially designed support wedge, Fig. 3, by clamping it from both sides of the wedge, and by applying tension to the wire from above. To bond 4-wire tether, we use a specially designed bonding wedge that holds all the three upper wires concurrently, Fig. 3. This 3-wire wedge permits us to bond three loop wires separately onto a single base wire. An industrial 60 kHz K&S 4123 ultrasonic wire bonder performs the actual bonding. Success of each bonding is confirmed optically using a Veho VMS-004D USB microscope camera with NI Labview based image acquisition software. This inspection system is incorporated into the production cycle. It stops the process if a bond fails and places a new bond next to the failed one. Successful bond formation is identified by requiring that the loop wire leaves the bond vertically as the upper wedge is retracted. This is determined by automatic image analysis.

Once bond formation has been confirmed, the wires are released, reeled on an output spool, and the factory is realigned in preparation for the next bond. During production, data on the bonding process is collected by the control software for post-production analysis. This includes one image of each bond obtained during the same phase of the production, bond count, and which wire is being bonded.

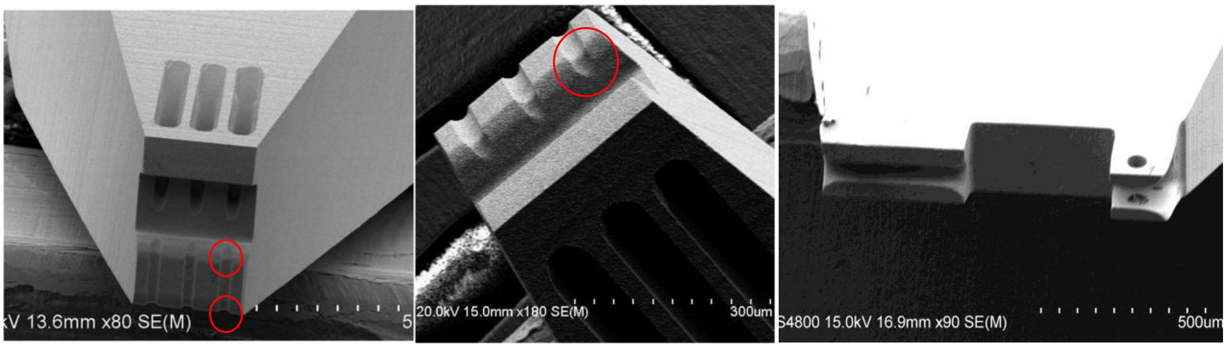


Figure 3. 3-wire bonding wedge (left and middle) and support wedge (right). Rounded edges on the grooves highlighted. SEM images 80X-180X magnification.

We set out to prove the capacity for full scale production by producing a 1 km long piece of Heytether that fulfills the ESAIL quality requirements [4]. This tether was reeled onto a standard Tanaka AL-2 50.3 mm diameter reel [7].

Six separate 15 m long tethers were produced in preparation for the first experimental test of the E-Sail effect. These tethers were manufactured with the same production parameters as the 1 km tether. After initial pull tests, one of the samples was selected as flight model, to fly with the EstCube-1 miniature satellite in March 2013, Fig 4.

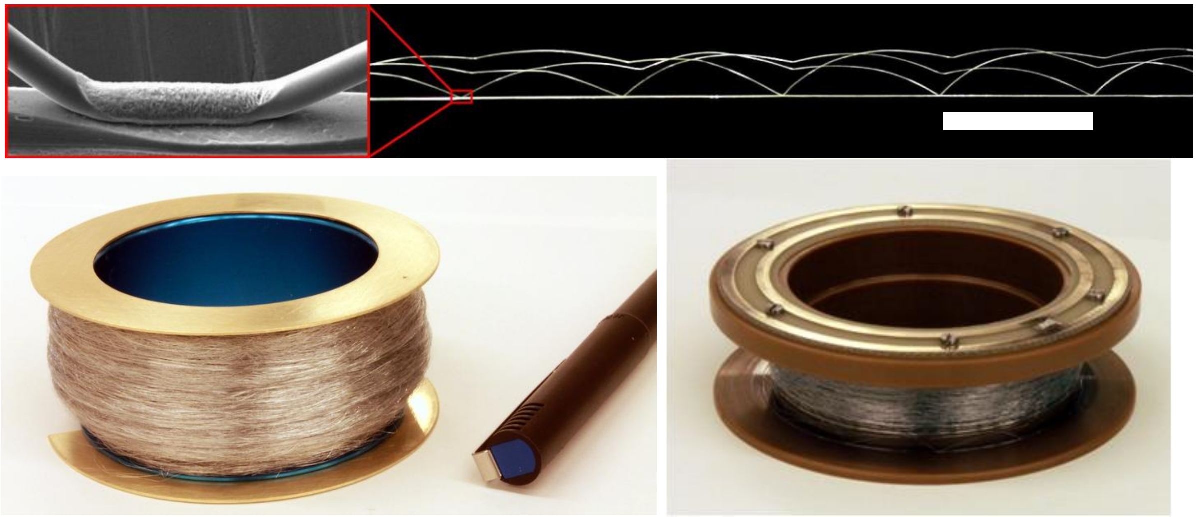


Figure 4. Close up of bond and part of the tether, scale bar is 1 cm (top). 1 km of tether on its output spool (bottom-left) and 15m tether on the flight reel (bottom-right).

Destructive pull tests were carried out on the other five 15 m long tethers. Four 1 m long samples from each of these tethers were pull tested. They were sampled at 5 m intervals, Fig 5. On average, 15 pulls were conducted for each of these samples.

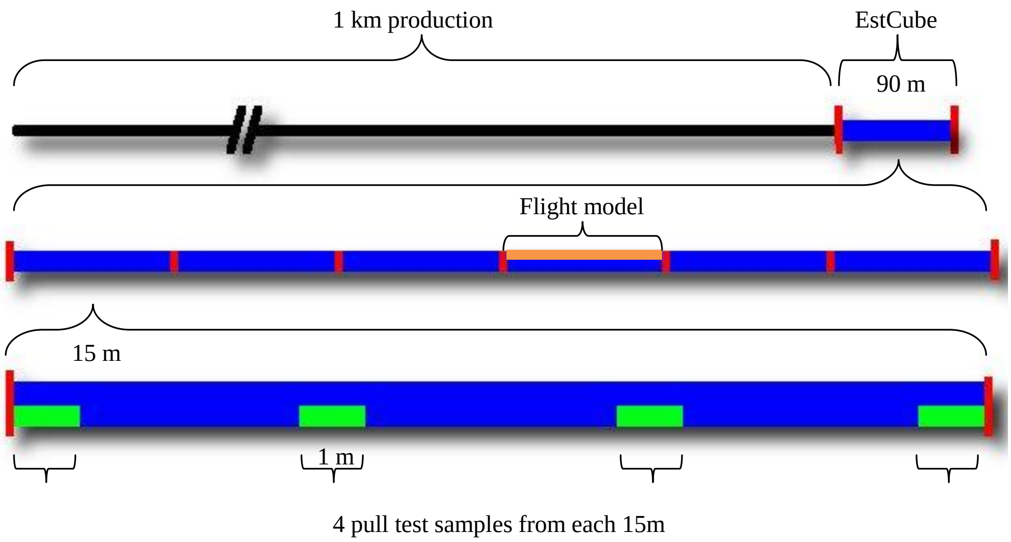


Figure 5. Sampling scheme for the pull tests.

Results With the Tether Factory we produced a continuous 1 km 4-wire Heytether containing 90700 wire-to-wire bonds, Fig 4. It took us three weeks to produce the tether. The working production speed was 3 m /hour (1 bond/12 sec) whereas the average production speed for the whole duration was 1.4 m /hour. The bonding wedge was cleaned seven times during the production.

The results of the image analysis are presented in Fig 6. These results show an increase in bond failure rate at the end of the wedge cleaning intervals. The failure rate levels off after the cleaning. Many unfixable bonds in succession is indicative of a mechanical fault in the tether factory.
In summary: 375 failed bonds of which 287 were automatically fixed, on average 1000 bond long stretches (ca 10 m) without fail, longest such stretch being 7600 bonds (ca 76 m). Post fix there were no 3-consecutive-fails whereas there were eight 2-consecutive-fails situations. Initially one

step motor malfunctioned (large fail rate), and a servo partially broke down at 71000 bonds (even though previous life time tests indicated that it should be able to handle 500.000+ movements, data not shown). Key learning point: wedge cleaning is crucial and needs to be performed every 150 m (15000 bonds). Currently we are looking into whether it is possible to predict in-line when this intervention must be done (event prediction).

Results of post production pull tests are presented in Fig 7. These results show that the factory produces sufficiently strong bonds also after the 1 km task. Since it also produced 10 g pull strength before we began the km production (data not shown), we conclude that the strength specification was fulfilled during the entire production. We also find that wedge fouling, Fig. 8., reduces bond strength in a manner correlating with the increased fail rate seen in Fig 6. By extrapolation we predict that cleaning the wedge every 150 m should ensure > 5 g pull strength. Finally we see that wedge cleaning restores the process to 10 g level.

We would like to point out that the pull strength of the Tanaka 25 µm AlSi(1%) bonding wire is 13-15g [7] compared to our highest measured pull strength during production (11.0 ± 0.4) g. A pull strength close to the wire's tensile strength is possible thanks to the specially designed bonding wedge. Especially close attention was paid to rounding the edges of the grooves in order to minimize the stress to the neck of the bonds, Fig. 3.

Our results show that the method works and that Heytether production can be automated to a degree where manufacture of a large-scale E-Sail is possible.

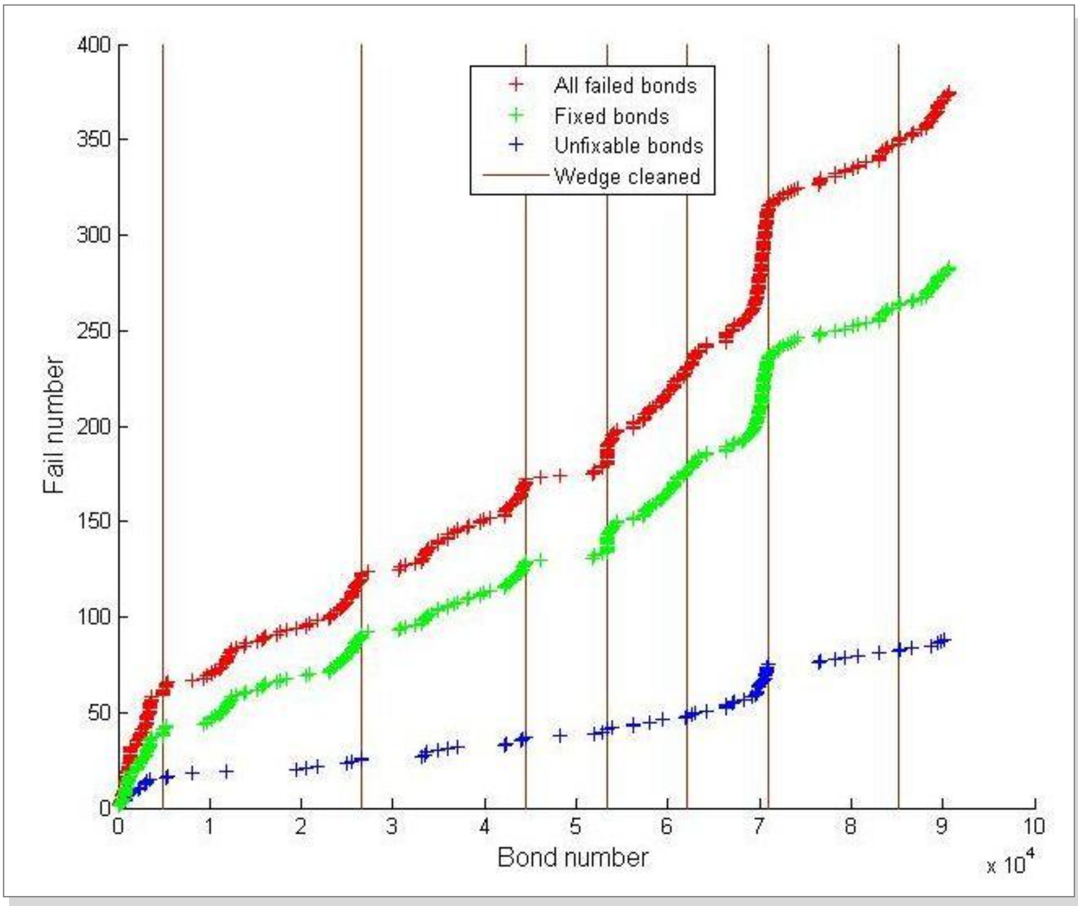


Figure 6. Failed and fixed bonds from the 1 km production data analysis.

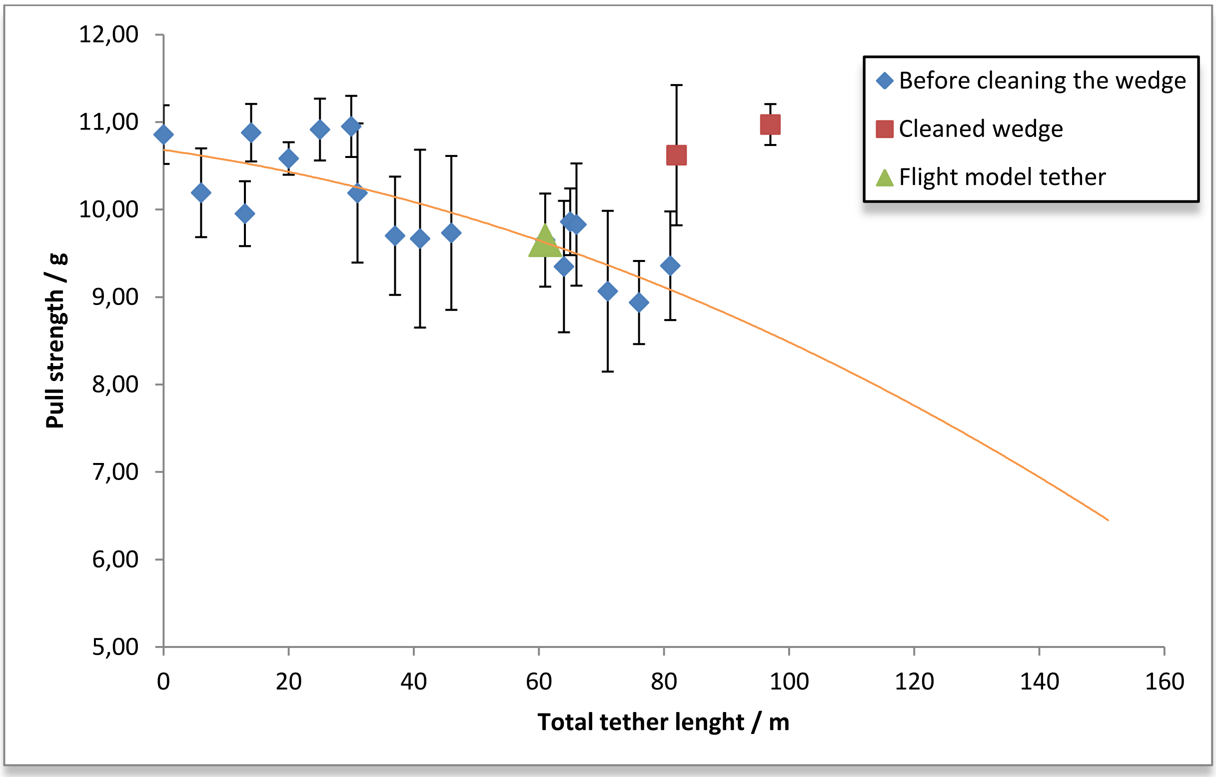


Figure 7. Measured average maximum sustainable pull force for EstCube tethers. A gradual decrease is seen as the total tether length increases. Five grams (5 g) represent the specified minimum pull strength. This extrapolation is supported by the production data in Fig 6.

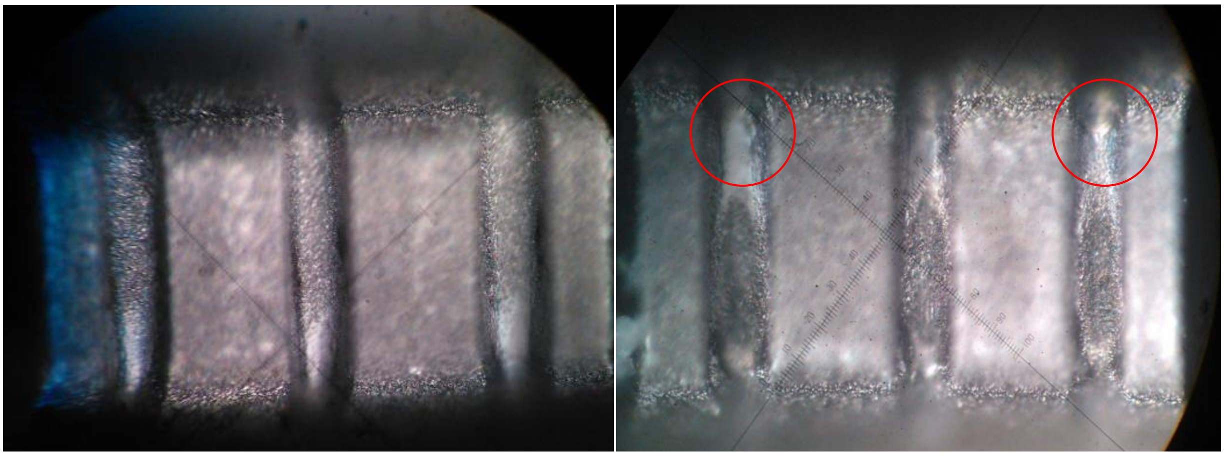


Figure 8. Clean (left) and fouled bonding wedge (right, 15000 bonds post cleaning). The grooves are contaminated with aluminum especially at the edges. Microscope images 500X magnification.

References

[1] Janhunen, P., *Electric sail for spacecraft propulsion*, J. Prop. Power, 20, 763-764, 2004.

[2] Mengali, G., A. Quarta and P. Janhunen, *Electric sail perfromance analysis*, J. Spacecr. Rockets, 45, 122-129, 2008.

[3] Hoyt, R. P., and Forward, R. L., *Alternate Interconnection Hoytether Failure Resistant Multiline Tether*, U.S. Patent 6286788, Issued 11 Sept. 2001.

[4] Janhunen, P. et al. *Electric solar wind sail: Toward test missions.* Rev. Sci. Instrum. 81, 111301 (2010).

[5] H. Seppänen, S. Kiprich, R. Kurppa, P. Janhunen, and E. Hæggström, *Wire-to-wire bonding of µm diameter aluminum wires for the Electric Solar Wind Sail*, Microelectronic Engineering, Volume 88, Issue 11, Pages 3267–3269, November 2011

[6] Kurppa, R. Ukkonen, J. Kiprich, S. Seppänen, H. Janhunen, P. Hæggström, E., *Method for electric solar wind sail tether production*,
European Planetary Science Congress 2010, held 20-24 September in Rome, Italy. http://meetings.copernicus.org/epsc2010, p.294

[7] http://www.mpenordic.com/Downloads/Tools%20and%20materials/Bonding%20wire%20Ver050307.pdf