Printed Heaters for Non-planar Space Applications

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1. Motivation
Typical Heater Applications on Spacecraft

Applications of high interest:

- Heating of spacecraft propellant lines (Ti-alloy tubes)
- Heating of curved surfaces (tanks, cylinders, etc.)
- Heater application on critical surfaces (CFRP structures, fibre wound spheres)
- Electrical grounding of electrically non conductive parts (plastics, CFRP panels, etc.)

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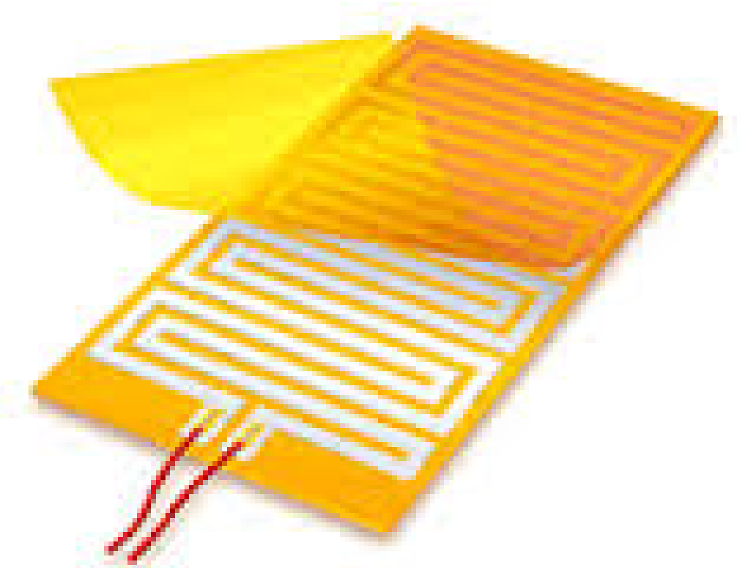
1. Motivation
Foil Heaters

Today:

- Etched foil resistive heating element laminated between flexible insulation (Polyimide, Silicone)
- Total thickness of ~ 0.4 mm or more
- Application by pressure sensitive adhesive

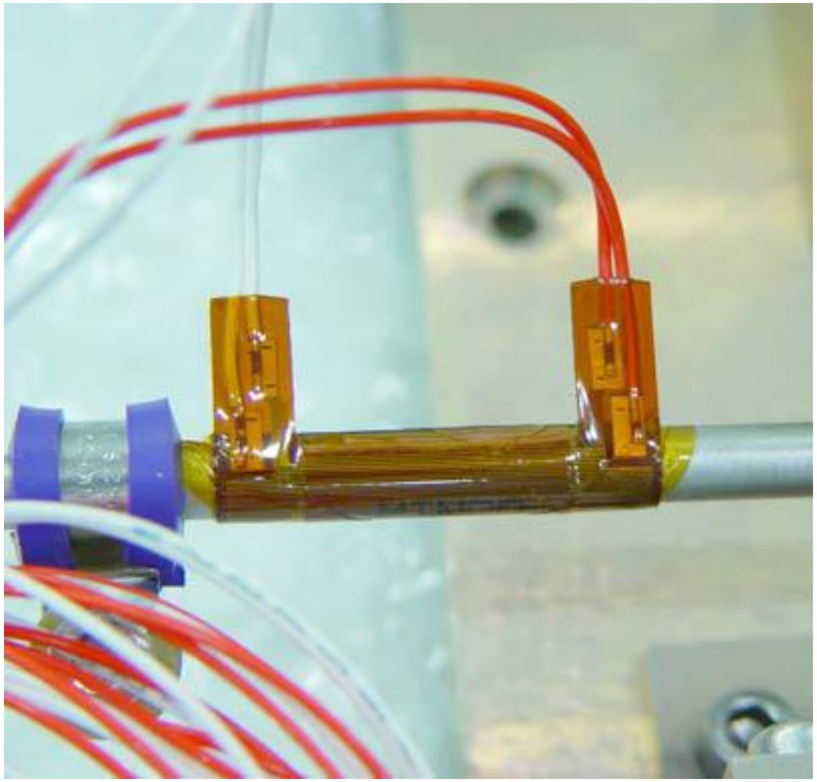


(© Minco)

1. Motivation
Foil Heaters

Issues with foil heaters:

- Bond failure of adhesive layer
  - Diff expansion of heater, adhesive, substrate
  - Inadequate surface preparation
  - Blister formation due to entrapped gas
- Curved surfaces
  - Stresses, strain by wrapping
  - Irregular surfaces (structural brackets) not possible



(wrapped foil heater around propellant line © OHB)

1. Motivation
Requirements for Space Heaters

Requirements, wish list for (printed) space heaters:

- Reliable, reproducible application procedure through automated process
- Reproducible, predetermined resistance values
- Operating temperature range adaptable to space needs
- Controlled, high reliability adhesion on various substrates (aluminium, titanium, CFRP)
- Free design of heater path configuration (large, short meander)
- Printing of wire connection points
- Heating of surface geometries of any shape
- High heating power possible with low supply voltage

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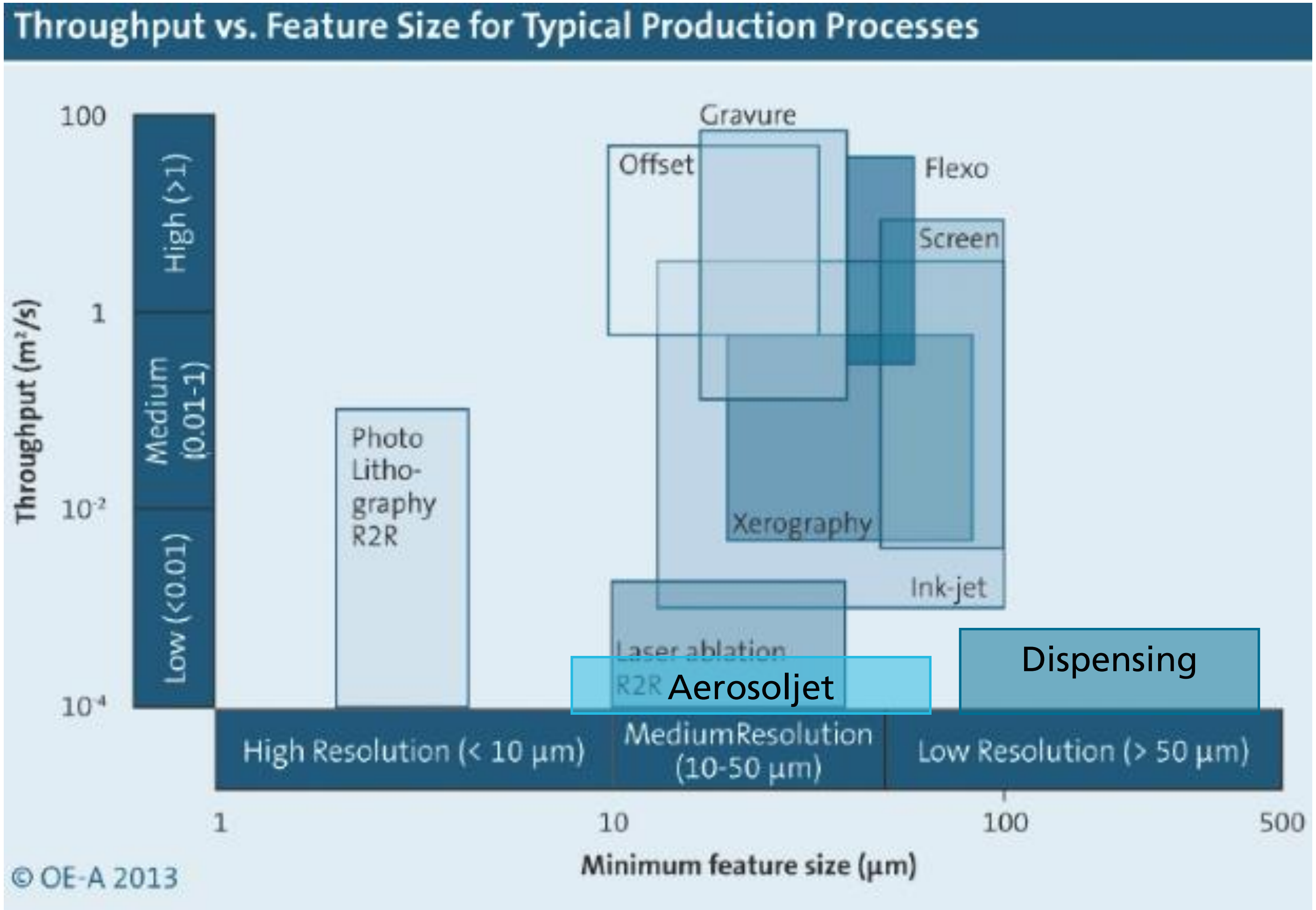
2. Printing of Heaters

Map of Printing Technologies



(© OE-A Roadmap for Organic and Printed Electronics, 5th Ed. 2013)

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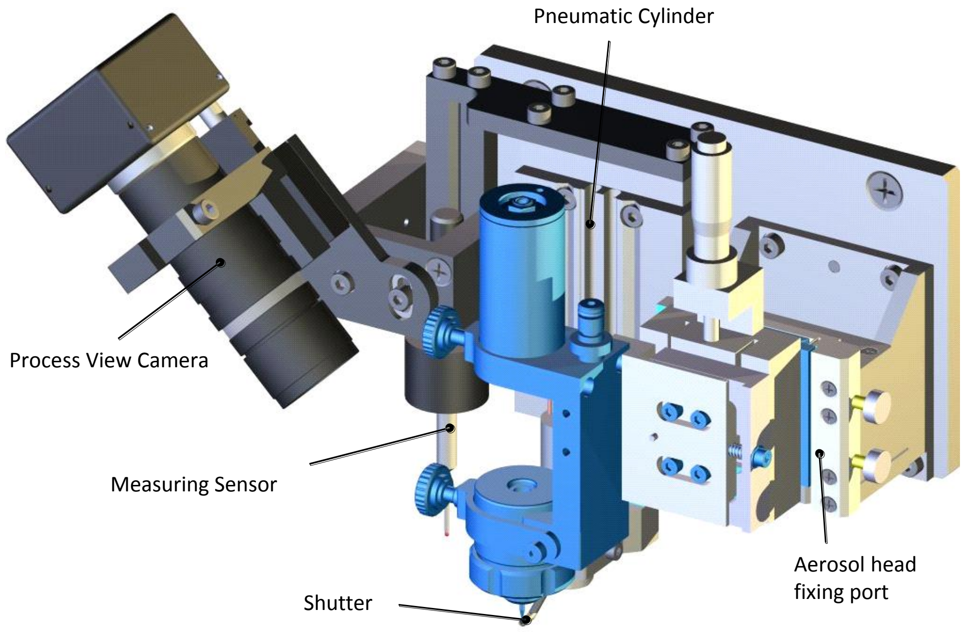
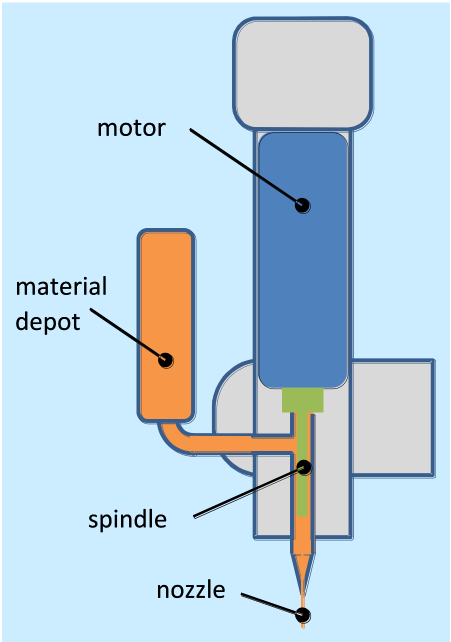
2. Printing of Heaters

Digital Printing Technologies for non-planar Surfaces

- Aerosoljet for smallest structures width > 10 µm, height > 1 µm

- Micro-Dispensing for structures width > 100 µm, height > 10 µm





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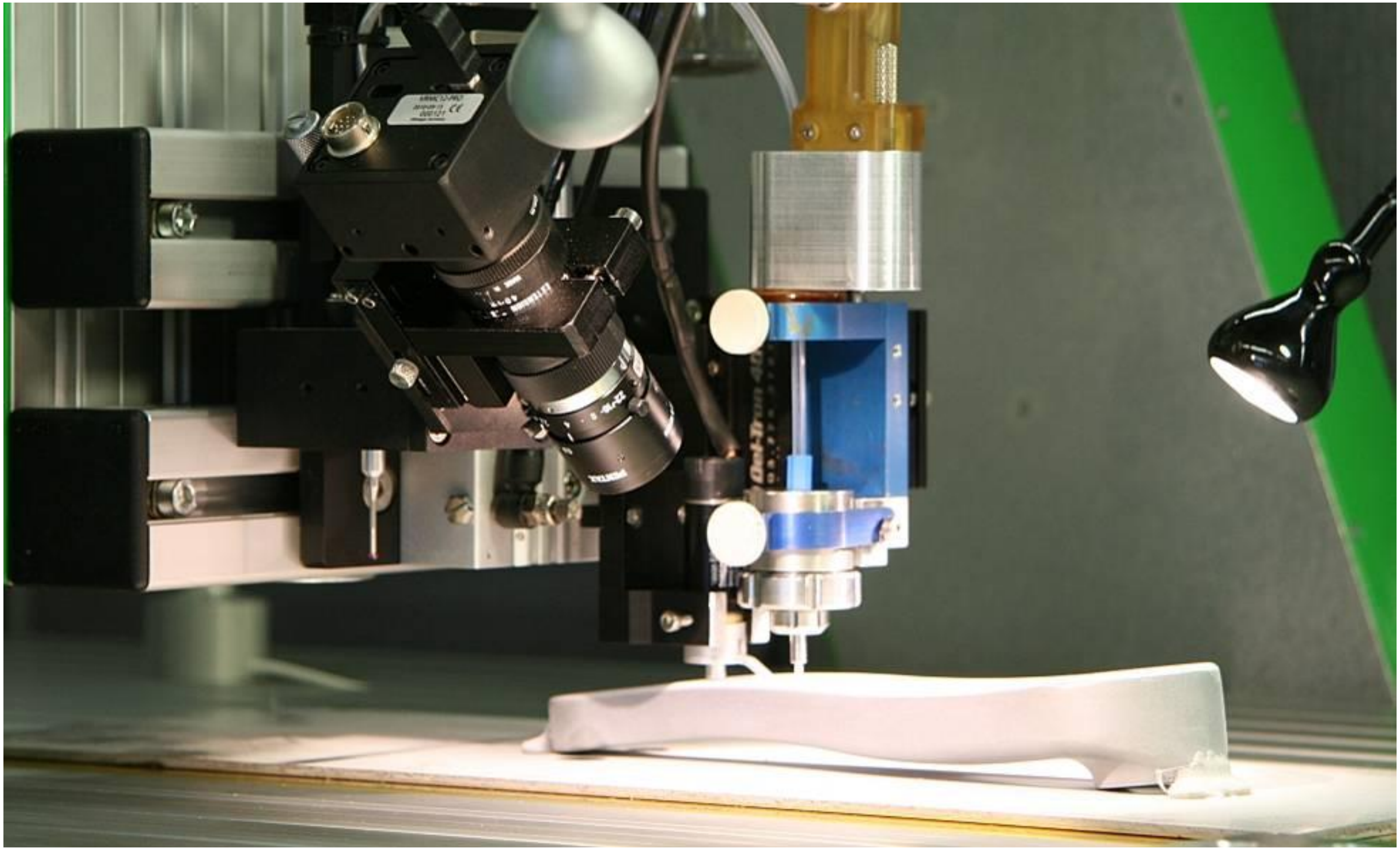
2. Printing of Heaters
Non-planar aerosol jetting of low viscous ink



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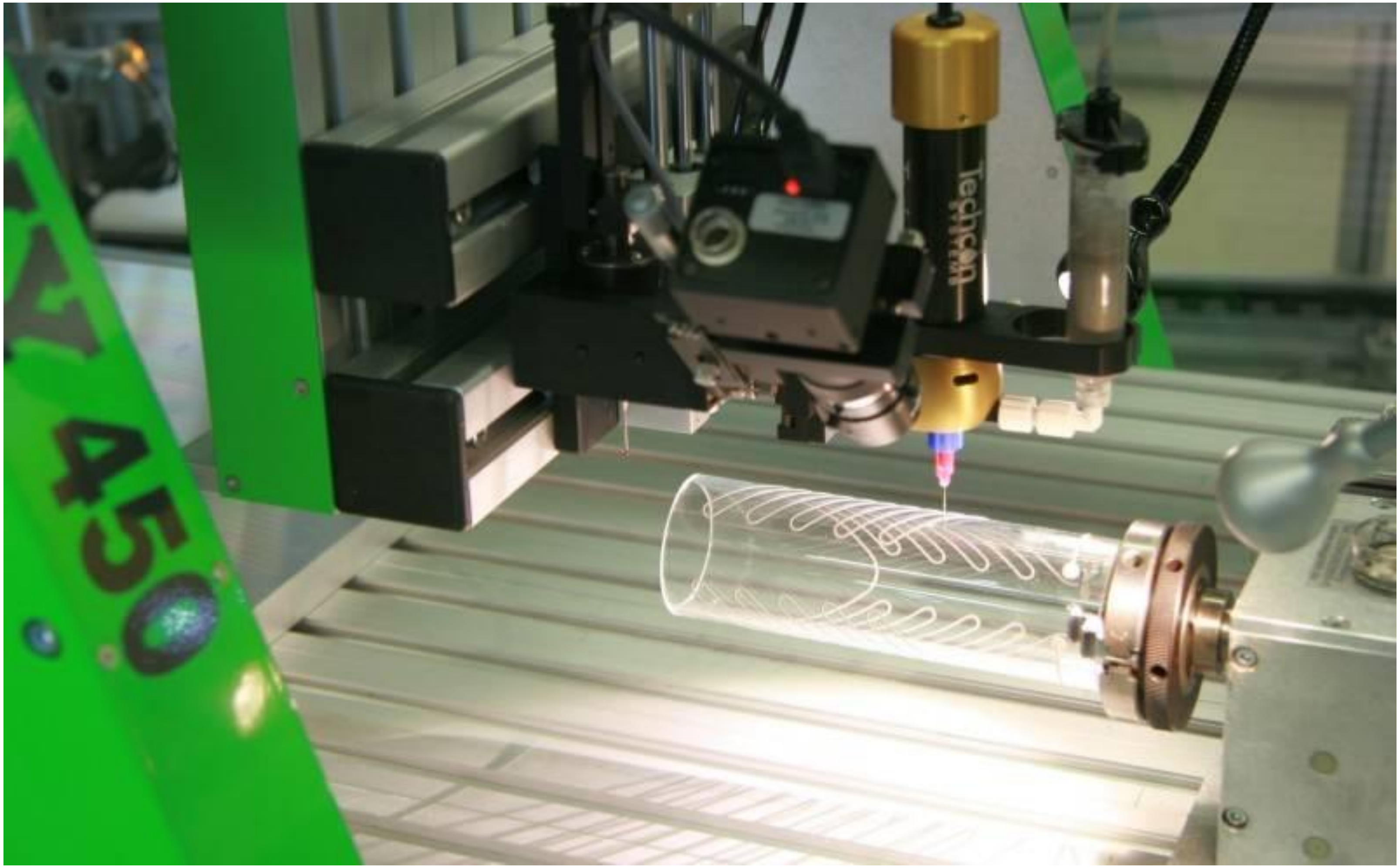
2. Printing of Heaters

Non-planar dispensing of high paste



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2. Printing of Heaters
Coating and Heating Materials

Insulation coatings

- Low pressure highly crosslinked polysiloxane-like plasma coating (CoverPLAS®, Fraunhofer IFAM)
- Fully imidized polyimid solution in N-ethyl pyrrolidon (P84, Evonik Fibres GmbH, Austria)

Heating tracks, Contacts

- Silver ink with nanometer sized particles in triethylene glycol monoethyl ether (Silverjet DGP-45-LT-15C, ANP Co Ltd, Korea)
- Silver screen printing epoxy paste (1901-SB, ESL Europe, UK)
- Silver-filled 2 K epoxy adhesive (Elecolit® 323, Panacol-Elosol GmbH, Germany)

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2. Printing of Heaters
Substrates

Substrate material (uncoated, as received)	Specifications	Electrical Resistance (25 °C, tip distance 100 mm)
Al 6061 sheet	EN AW 6061/T6, thickness 0.65 mm	~ 1–2 Ω
Al 5754 sheet	EN AW 5754, thickness 1.5 mm	~ 0.5 Ω
Al 2024 sandwich panel	Face sheet AL 2024 T81, thickness 0.3 mm	~ 1 Ω
CFRP sandwich panel	Face sheet M55J/LTM123, 80 g/m², 33% RW, thickness 0.3 mm	~ 1–10 kΩ
Thermoplast curved	CF/PEEK with AS4 fibres	~ 0.2–2.0 kΩ
Ti propellant tubing	Ti 6Al-4V, 6.5 mm OD	~ 0.2 Ω

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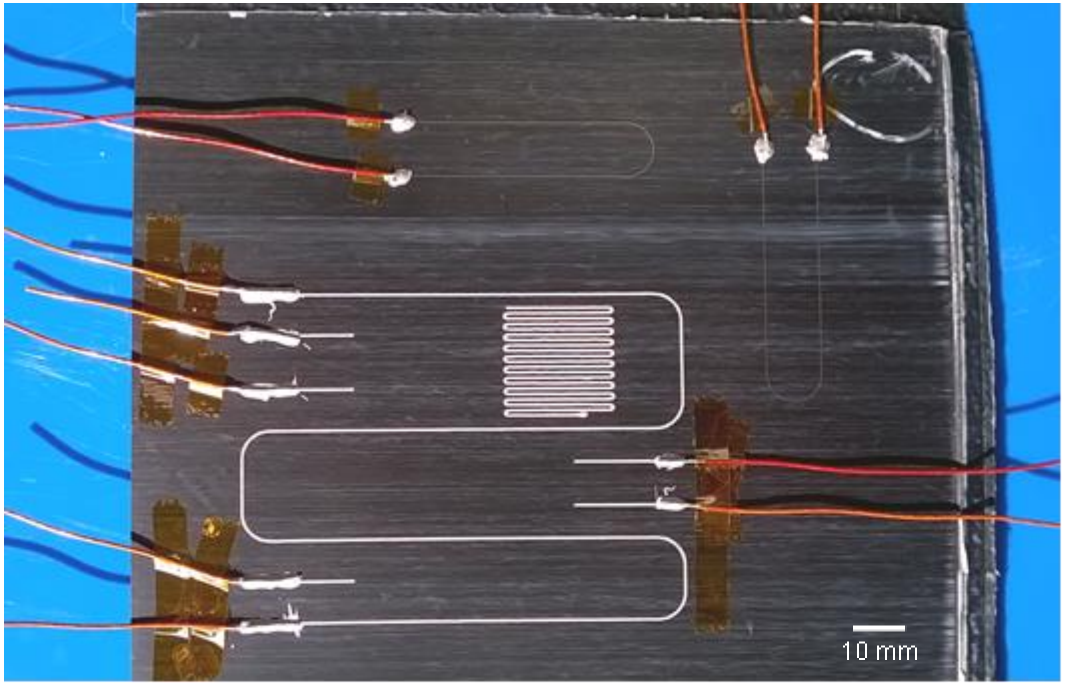
2. Printing of Heaters
Preparation of Test Samples

- Curved CF/PEEK with contacted dispensed and aerosol jetted heaters and test structures for pull-out test and cross-cut test on plasma coating



- Titanium alloy tube with aerosol jetted and contacted heating track on polyimide coating

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2. Printing of Heaters
Dimensions and Electrical performance

- Coating thickness and electrical insulation behaviour

Coating	Parameters	Thickness	Insulation Resistance IR Coating/coating	Insulation Resistance IR coating/track
IFAM Plasma	CH_PA7_161215	3.7 ± 0.3 µm	> 260 GΩ (@500 V)	often shorts
P84 spin coating	2000 rpm	9.4 ± 0.5 µm	> 260 GΩ (@500 V)	> 260 GΩ (@500 V)
P84 spin coating	2500 rpm	8.7 ± 0.4 µm	> 260 GΩ (@500 V)	> 260 GΩ (@500 V)
P84 spin coating	3000 rpm	7.4 ± 0.2 µm	> 260 GΩ (@500 V)	> 260 GΩ (@500 V)

- Heating track characteristics and electrical resistance

Heater Material	Printing Process	Mean Track Width	Max. Track Height	Electrical Resistance
Ag ink	Aerosoljet 2x, v = 2 mm/s	83 ± 7 µm	2.3 ± 0.4 µm	2800 Ω/m
Ag ink	Aerosoljet 3x, v = 1 mm/s	56 ± 6 µm	3.0 ± 0.6 µm	1200 Ω/m
Ag paste	Needle dispensing ø 0.1 mm, v = 0.6 mm/s	458 ± 61 µm	17 ± 1 µm	155 Ω/m
Ag paste	Needle dispensing ø 0.1 mm, v = 0.6 mm/s	451 ± 17 µm	16.5 ± 0.5 µm	115 Ω/m
Ag paste	Vermes jetting ø 0,15 mm, v = 9 mm/s	1198 ± 32 µm	65 µm	12 Ω/m

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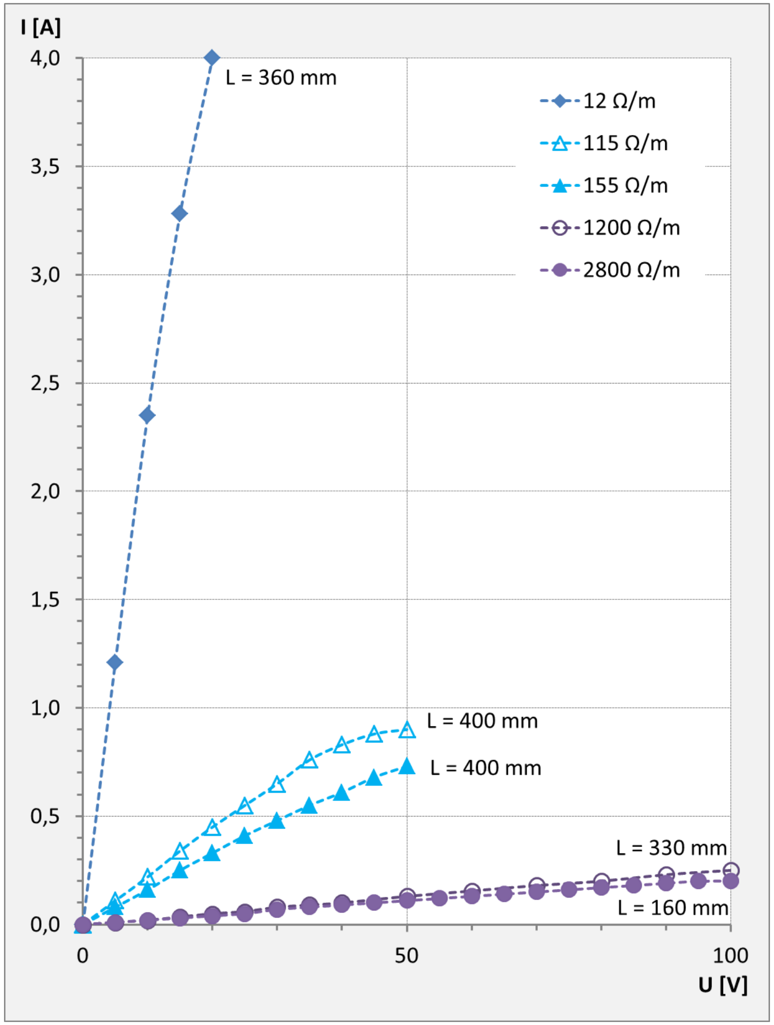
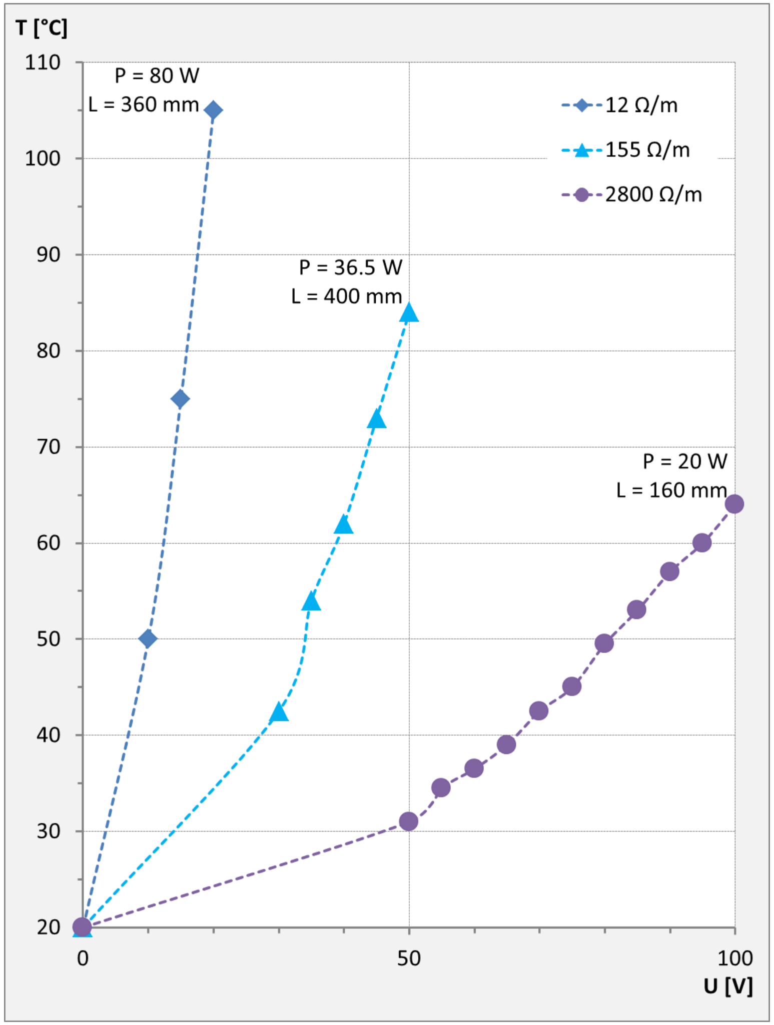
3. Characterisation and Performance

Heating tests at RT





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3. Characterisation and Performance
Heater failure modes

- needle dispensed heater failed at 50 V due to inhomogeneity of paste

- aerosol jetted heater contact failed at 75 V due to insufficient electrical insulation towards the aluminium substrate

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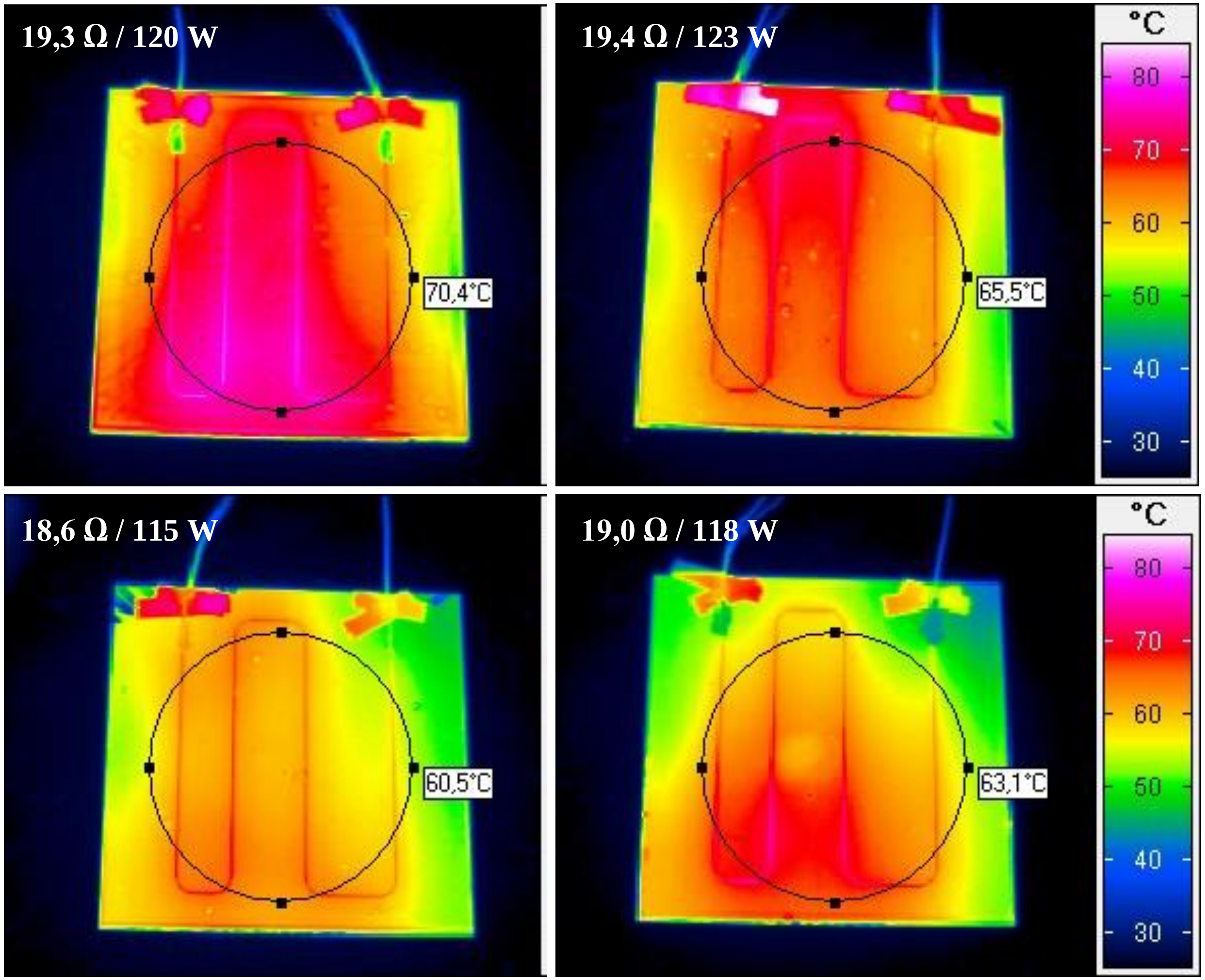
3. Characterisation and Performance
Heating tests at RT

- Dispensed Ag-paste on polyimide coated aluminium sheet
- 4 identical prepared samples
- ~ 400 mm length
- 50 V, ~ 120 W



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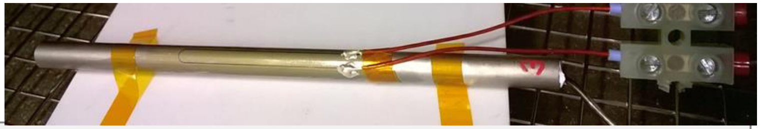
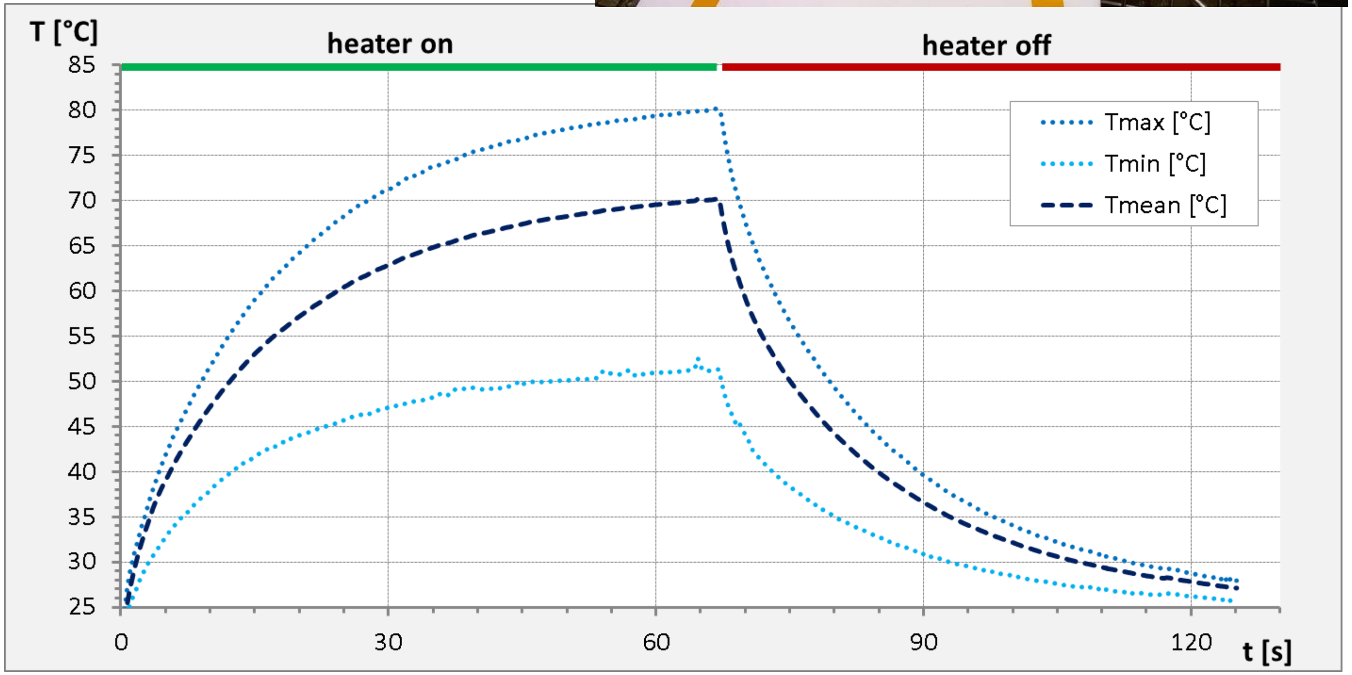
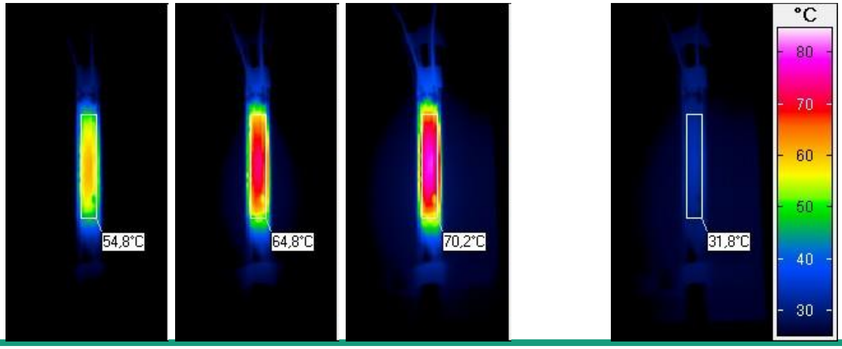
3. Characterisation and Performance

Heating tests at RT



- Aerosol jetted Ag-ink on polyimide coated Ti-tube
- 80 mm length
- 10 V, ~ 2 W





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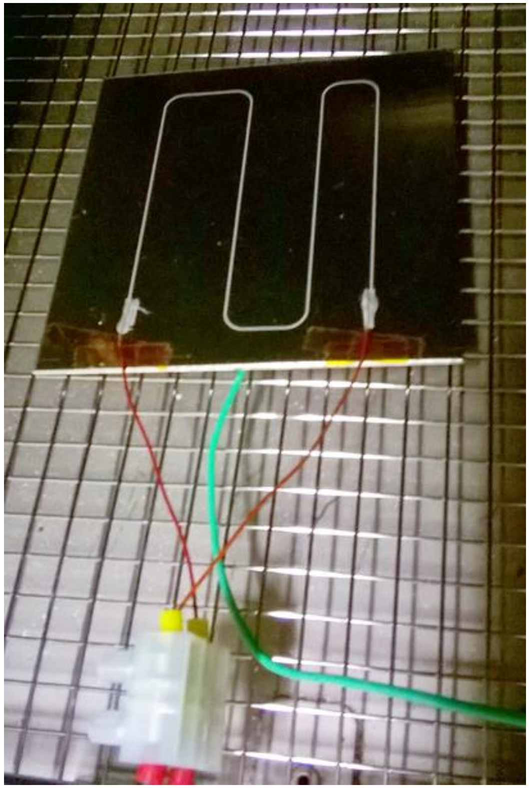
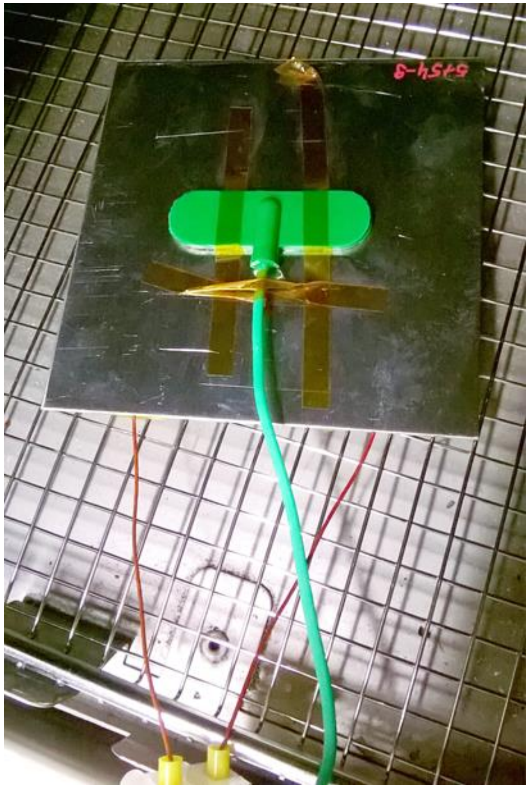
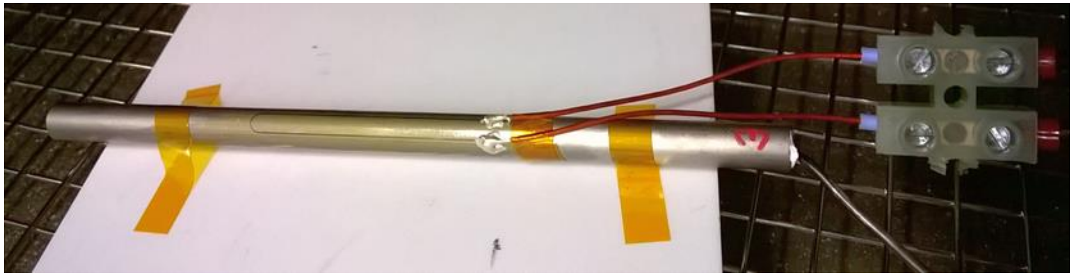
3. Characterisation and Performance

Thermal cycling

- 2 dispensed heaters on aluminium sheet 100 x 100 cm²
- 1 aerosol jetted heater on ti-tube 6.5 mm, 10 cm
- Thermocouple mounted on the back/inside







3. Characterisation and Performance
Thermal cycling

- 200 cycles -65/+65 °C in air
- Additionally heater on within change from cold to warm
- Electrical resistivity slightly decreases

sample	*Coating and heater*	$R_{50\ cycles}$	$R_{100\ cycles}$	$R_{150\ cycles}$	$R_{200\ cycles}$
5754-8	Dispensed Ag on P84 coated aluminium sheet	45,1 Ω/m	45,7 Ω/m	43,9 Ω/m	43,4 Ω/m
5754-9	Dispensed Ag on P84 coated aluminium sheet	42,0 Ω/m	40,8 Ω/m	39,6 Ω/m	38,3 Ω/m
Ti-3	Aerosol jetted Ag on P84 coated Ti tube	656 Ω/m[1]	628 Ω/m	-	622 Ω/m

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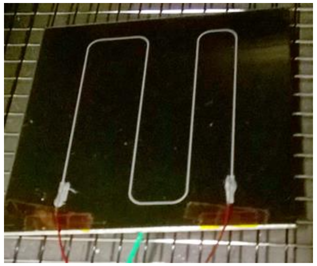
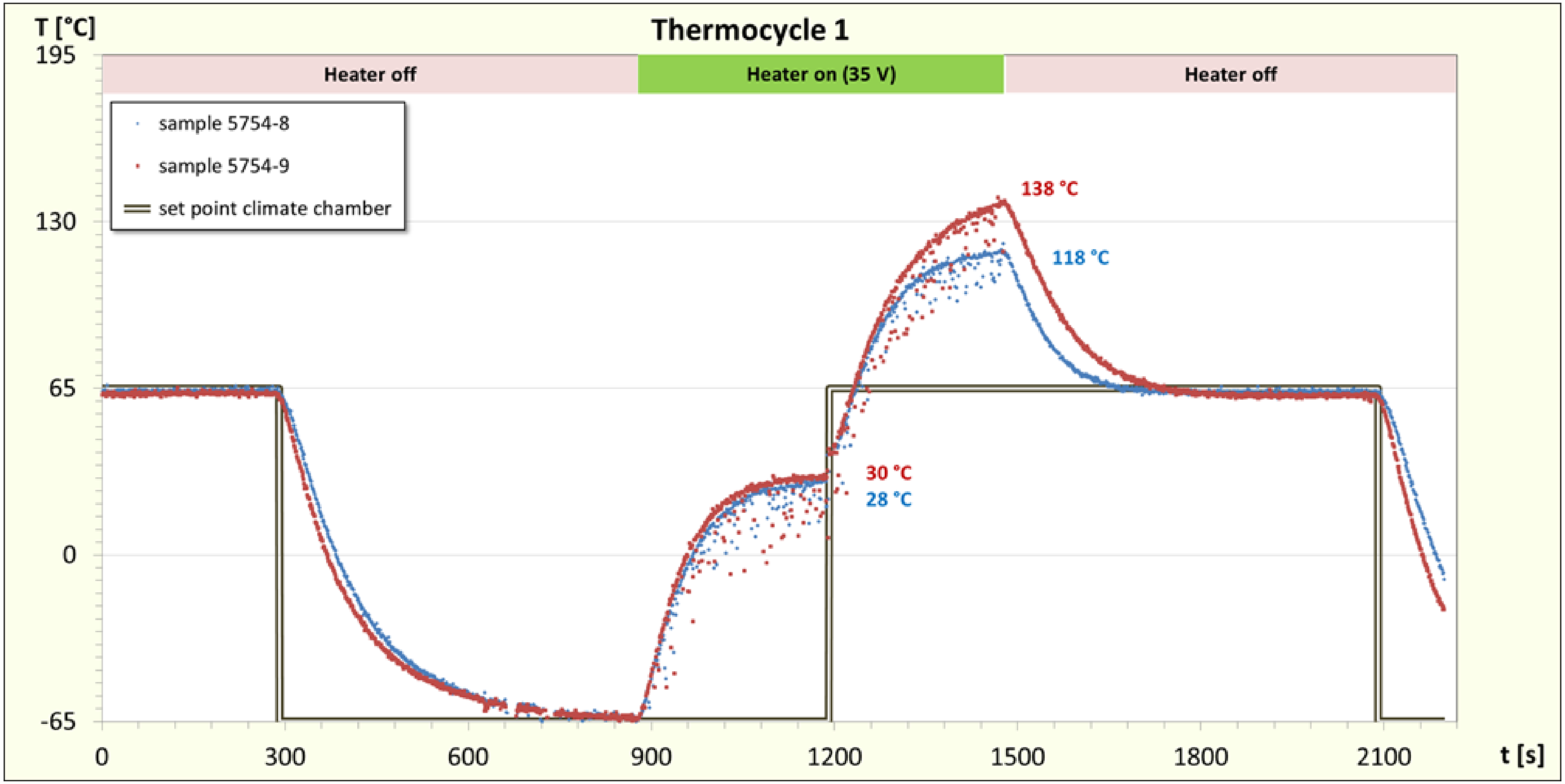
3. Characterisation and Performance
Thermal cycling



- Dispensed heater on aluminium sheet, cycle 1



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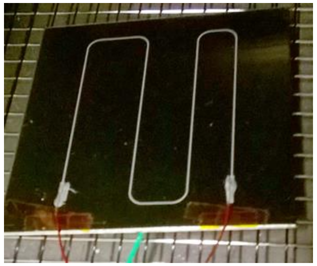
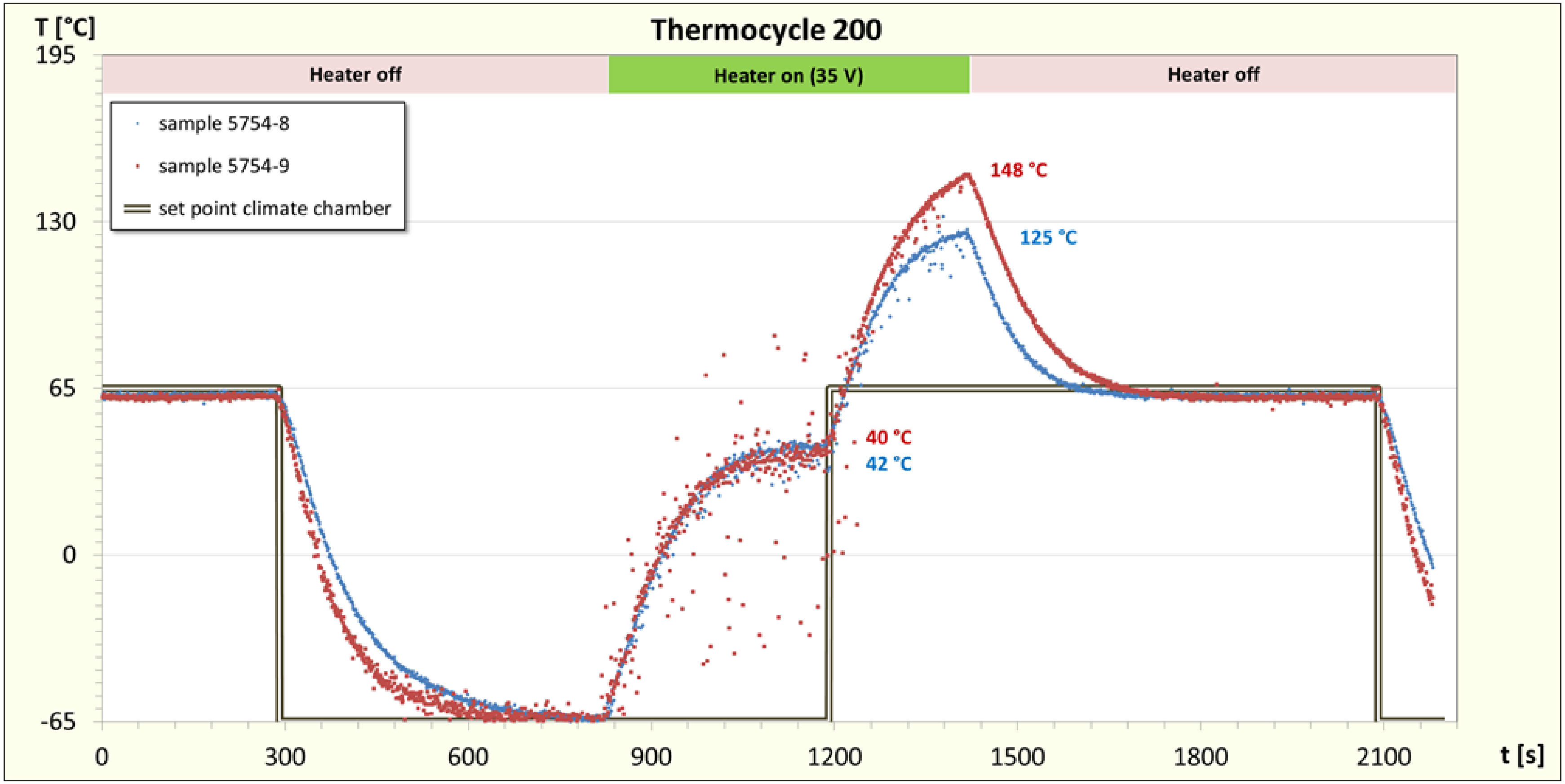
3. Characterisation and Performance
Thermal cycling



- Dispensed heater on aluminium sheet, cycle 200



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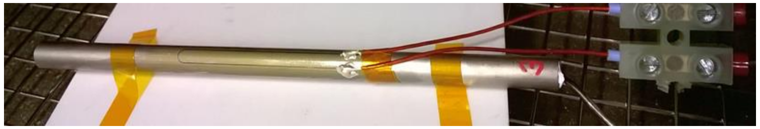
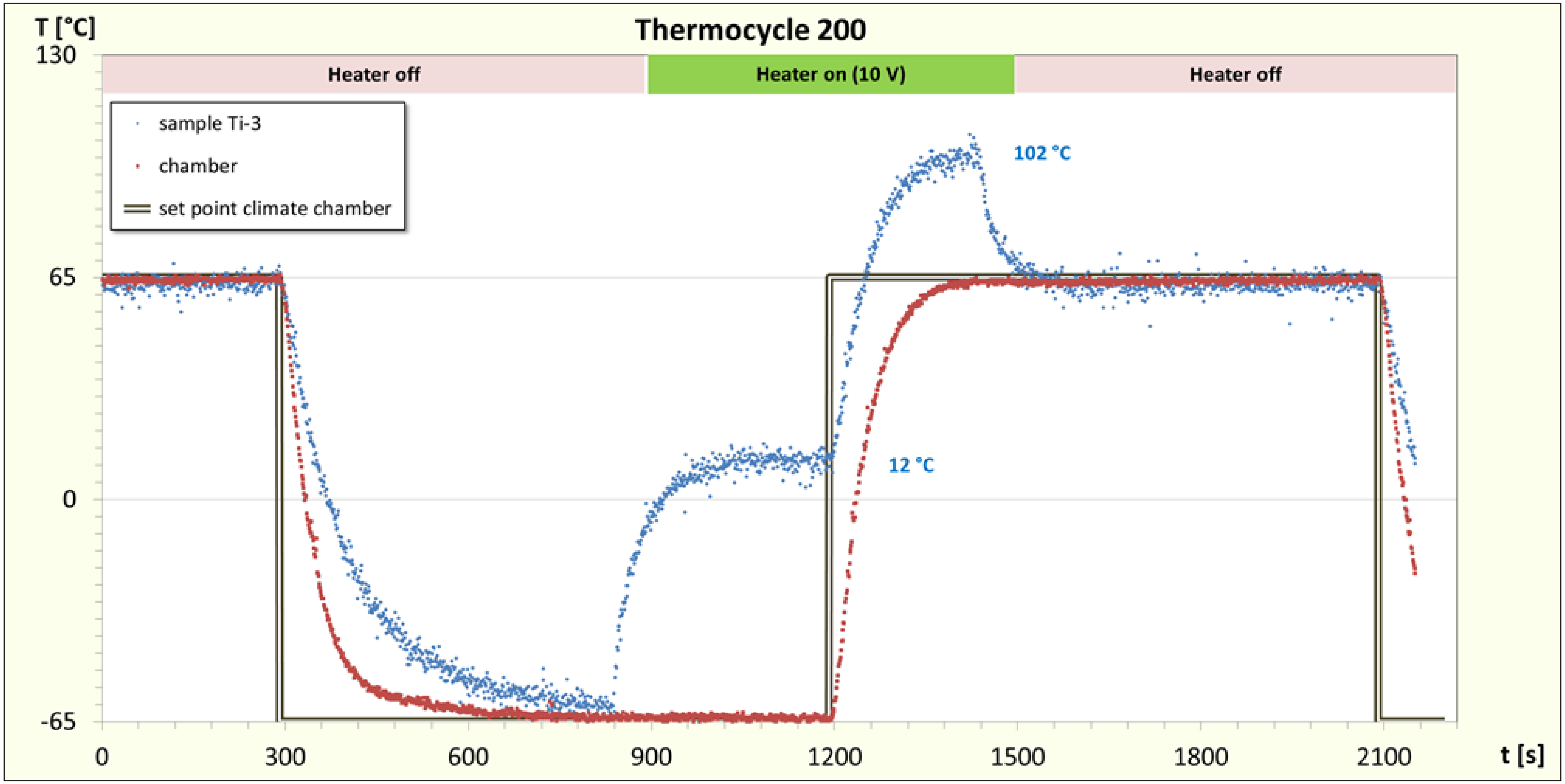
3. Characterisation and Performance
Thermal cycling



- Aerosol jetted heater on titanium alloy tube, cycle 200



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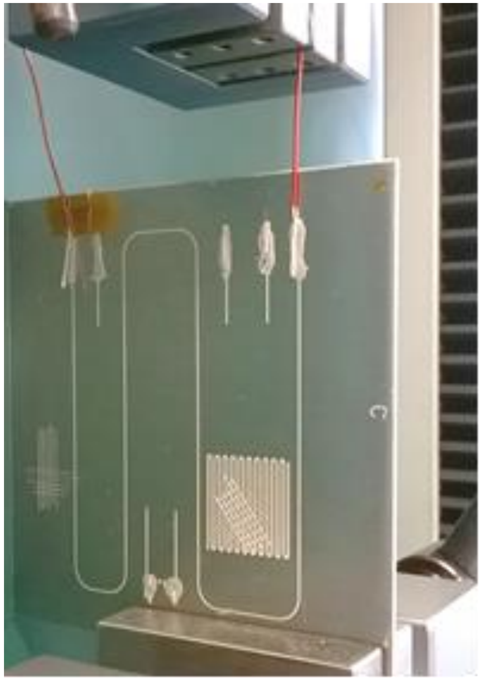
3. Characterisation and Performance
Lead pull strength

- MIL-STD-202G, Method 211A, Test Condition A at 1,36 kg
- silver plated copper wire qualified according to ESCC 3901/019 (SPL 10-26-C AWG26, W. L. Gore & Associates, Inc.)
- Embedding lengths 5 and 10 mm



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3. Characterisation and Performance

Lead pull strength

Embedding material	Coating of substrate	Embedding wire length	No. of samples	Pull-out strength (mean value)
Elecolit 323	IFAM Plasma on aluminium	5 mm	2	47.6 N
Elecolit 323	IFAM Plasma on CFRP	5 mm	2	–[1]
Elecolit 323	P84 on aluminium	5 mm	2	38.9 N
1901-SB	IFAM Plasma on aluminium	5 mm	2	15.7 N
1901-SB	IFAM Plasma on aluminium	10 mm	3	29.3 N
1901-SB	P84 on aluminium	5 mm	2	13.0 N
1901-SB	P84 on aluminium	10 mm	4	29.4 N
1901-SB	IFAM Plasma on CFRP	5 mm	2	19.6 N
1901-SB	IFAM Plasma on CFRP	10 mm	3	23.8 N
1901-SB	IFAM Plasma on CF/PEEK	5 mm	1	5.3 N
1901-SB	IFAM Plasma on CF/PEEK	10 mm	4	25.7 N

Elecolit 323

1901-SB

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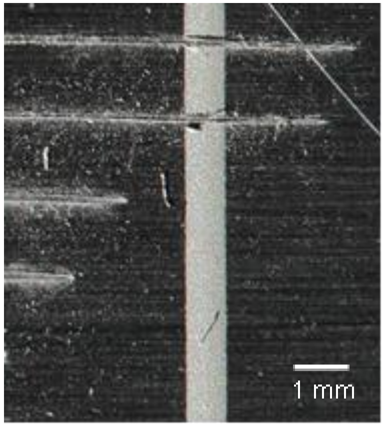
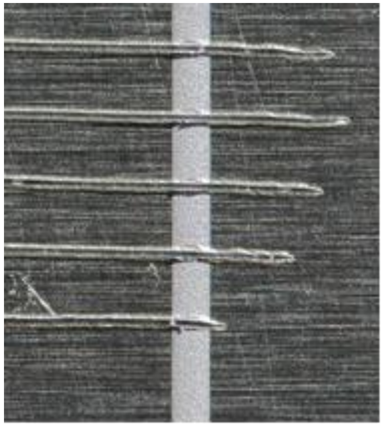
3. Characterisation and Performance
Adhesion testing

- Testing of adhesion of coatings and printed heating tracks
- ISO-2409: 2007 "Paints and varnishes - Cross-cut test"



Plasma coating on aluminium



Polyimide coating on aluminium

Plasma coating on CFRP

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3. Characterisation and Performance
Outgassing tests

- Outgassing tests of used materials are planned at ESTEC facilities

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4. Résumé for space applications

Summary

- Tailored electrical resistances (10 to 1000 Ω/m) and heating performance by printing on space relevant surfaces
  - Pure metal track heaters
  - Metal-epoxy track heaters
- Electrical insulation coating necessary
  - P84 showed best performance, but no adhesion on CFRP
  - Plasma coating inhomogeneous towards borders, edges
- Adhesive bonds of heating tracks and cables mostly strong enough but weaker/not as reproducible on CFRP
- Devices withstand thermal cycling
- All tests were done without top coating

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4. Résumé for space applications
Outlook

- Future integration of heaters off-line possible

- Enhance quality by in-line printing process control
- Use alternative printing technologies
  - For planar surfaces screen printing = faster, higher reproducibility
- Use alternative metal heater materials (NiCr, …) with different electrical resistances
- Printing of temperature sensors
  - With same materials and processes
  - Only different layout

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Thank You!

- Questions?

- Acknowledgments
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