Scientific publications, presentations and posters for the basis of theses

[C1] **Z. Tóth**, I. Szalai and A. Lukács,” Ionic contamination reduction with dry ice cleaning,” IOP Conference Series: Materials Science and Engineering (1757-8981 1757-899X): 1246 1 p. 012015. (2022) https://doi.org/10.1088/1757-899X/1246/1/012015

[C2] **Z. Tóth**, E. Kocsis, A. Lukács, and I. Szalai, “‘No-Clean’ Flux Residues Detection With Impedance Measurements,” IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 14, no. 4, pp. 729–734, Apr. 2024, https://doi.org/10.1109/TCPMT.2024.3382098

[C3] Z. Ható, B. Horváth, S. Guba S, **Z. Tóth**, E. Kocsis, D. Boda. and I. Szalai, “Electrochemical migration and dendrite growth between two electrodes: Experiments and Brownian dynamics simulations,” International Journal of Heat and Mass Transfer, vol. 234, p. 126108, Dec. 2024, https://doi.org/10.1016/j.ijheatmasstransfer.2024.126108

[C4] **Z. Tóth**, E. Kocsis, A. Lukács, and I. Szalai, “No-clean flux residues detection with impedance measurements,” Proceedings of the 19th IMEKO TC10 International Conference on Measurement for Diagnostics, Optimization and Control on Measurement in Testing, Inspection and Certification, pp. 81–85, 2023, https://doi.org/10.21014/tc10-2023.012

[K1] **Tóth, Zs.;** Szalai, I. és Lukács, A.: Szárazjeges tisztítás lehetőségei az autóelektronikai gyártástechnológiában, ENELKO 2022 - XXIII. Nemzetközi Energetika-Elektrotechnika Konferencia, SzámOkt 2022 - XXXII. Nemzetközi Számítástechnika és Oktatás Konferencia, Erdélyi Magyar Műszaki Tudományos Társaság (EMT), (2022) pp. 60-64., 4 p., ENELKO, Marosvásárhely, Románia, 2022. október 13-16. https://ojs.emt.ro/index.php/enelko-szamokt

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1. **Tóth, Zs.**: Fourier-transzformációs infravörös (FTIR) spektroszkópia alkalmazása az elektronikai gyártás területén, XII. Roncsolásmentes Anyagvizsgáló Konferencia és Kiállítás (RAKK) és 10. Anyagvizsgálat a Gyakorlatban (AGY) Konferencia, Online, 2021. március 17-19.
2. **Tóth, Zs.**; Szalai, I és Lukács, A.: Ionos szennyezettség csökkentése szárazjeges tisztítással, XIII. Országos Anyagtudományi Konferencia, Balatonkenese, 2021. október 10-12
3. **Tóth, Zs.**; Lukács, A. és Szalai, I.: Szárazjeges tisztítás ionos szennyezettség csökkentő hatásának vizsgálta, PhD hallgatók anyagtudományi napja XXI., Veszprém, 2021. november 8.
4. **Tóth, Zs.**; Lukács, A. és Szalai, I.: Szárazjeges tisztítás alkalmazása az elektronikai gyártástechnológiában, PhD hallgatók anyagtudományi napja XXII., Veszprém, 2022. november 14.
5. **Tóth, Zs**; Kocsis E.: Elektronikai szerelvények forraszthatóságának növelése, Tudománynapi Konferencia a Zalaegerszegi Egyetemi Központban, Zalaegerszeg, 2022. november 16.

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Increasing the efficiency and reliability of the cleaning process of automotive electronic assemblies

Ph.D. THESIS

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Introduction

Ionic contamination has been a critical problem for manufacturers of electronic assemblies since the beginning. The function of fluxes is to deoxidize the metals involved in soldering and to promote proper wettability to create an optimal soldered joint. In automotive electronics manufacturing technology, the no-clean fluxes are commonly used during the soldering process. This can give a false sense of security and create the illusion that the product is clean after soldering. However, weak organic acids and other residues can promote failures due to electrochemical migration and corrosion.

Cleaning and washing the products after soldering was a daily practice in the electronics industry until the end of the last century. Part of the problem with modern flux is that if we don't clean the flux residue, we don't clean anything else. The quality of the panel surfaces can be deteriorated by other pollutants besides flux residues. Ionic and organic contaminants originate from many sources and can jeopardize the panel in many forms during the manufacturing process. Cleaning all contaminants is crucial to achieving predictable performance. However, aqueous, solvent washing is often not feasible as it can damage the moisture-sensitive systems of modern electronic products in unpredictable ways. Therefore, waterless, but non-destructive cleaning methods such as compressed air cleaning, plasma cleaning, or the dry ice and snow blasting, which is a focus of research, may be practical.

The standard testing methods are no longer sufficient – due to miniaturization and higher component density – in case of modern automotive systems. The debate about which standards and cleanliness test method to use has intensified recently. Standards are expanding to include a more comprehensive definition of cleanliness. Ion chromatography (IC), resistivity of solvent extract (ROSE), and surface insulation resistance (SIR) testing are all useful tools for determining whether a unit is clean or not, but each has its disadvantages. The measurements are usually not repeatable, as the cleanliness of the assembly changes during the test.

Therefore, the non-destructive monitoring of the contamination level of safety-critical products and, if necessary, “agent-free” cleaning can be crucial to achieving the expected service life and reliable operation.

4. I have established that the dynamics of dendrite formation caused by electrochemical migration can be modeled with hybrid Brownian dynamics simulation, where the motion of the particles is determined by the following Langevin equation:

$$m_i \frac{dv_i(t)}{dt} = \left(\sum_j (\mathbf{f}_{ij}^{\mathrm{C}} + \mathbf{f}_{ij}^{\mathrm{WCA}}) + \mathbf{F}_i^{\mathrm{appl}} \right) - m_i \gamma_i \boldsymbol{v}_i(t) + \boldsymbol{R}_i(t),$$

where $-m_i \gamma_i \boldsymbol{v}_i(t)$ is the friction force,

$\boldsymbol{R}_i(t)$ is the random force,

$\boldsymbol{v}_i$, mi and γ_i are the position, velocity, mass and friction coefficient of particle *i*.

The systematic forces are the Coulomb force $(\mathbf{f}_{ij}^{\mathrm{C}})$ and the Weeks-Chandler-Anderson force $(\mathbf{f}_{ij}^{\mathrm{WCA}})$, as well as the applied forces ($\mathbf{F}_i^{\mathrm{appl}}$) exerted by the walls and dendrites.(Relevant Publications: **[C3]**)

4.1. I concluded from the simulations that the initial rate of dendrite growth is lower and the process accelerates as the dendrites approach the anode.

4.2. The dendrite growth dynamics observed in the simulation are consistent with experimental findings. Increasing the electric field strength or free Sn^{2+} ion concentration results in a decrease in the time to formation (TTT) of the conducting dendrite (short-circuiting).

3. I have developed a method based on impedance (capacitance) measurement that is capable of detecting and measuring flux residues on the surface of interdigital structures. This method may enable the monitoring of the usability of fluxes and the rapid qualification of the effectiveness of cleaning processes. Capacitance/resistance spectra were collected from PCBs supplied with a 2V amplitude AC signal between the terminals, using a C_P-R_P equivalent circuit model in the frequency range of 20 Hz to 1 MHz. I investigated the change in the surface capacitance of the system under different contamination conditions under the influence of a defined signal (2V, 5kHz) using a circuit based on the AD5934 IC. This method allows for the monitoring of the usability of fluxes and the rapid qualification of the efficiency of cleaning processes. (Relevant Publications: **[C2], [C4]**)

3.1. The electrochemical testing of ethanol-based weak organic acids (WOAs) containing "no-clean" (OR/L0) fluxes revealed a clear correlation between the amount of residue and the measured impedance values. After the climatic and storage tests, the flux residues were detected by ionic contamination measurement, visually and with impedance tests.

3.2. I observed a measurable difference in the capacitance of all flux-treated contaminated samples, which is caused by WOA residues accumulated in the gaps of the „copper defined" pads.

3.3. The analysis of the impedance spectra reveals a significant increase in the capacitive term and a decrease in the resistance at low frequencies (20-5000 Hz). Freshly dried samples show a similar behavior to the heat-treated samples, which is due to the presence of only partially activated flux residues. At higher frequencies (above 10000 Hz) the effect was less significant. I determined that the examination of capacitance values measured at a frequency of 5 kHz is optimal for detecting surface contamination.

3.4. By performing capacitance measurements at a specific frequency (5000 Hz) using an Impedance Converter IC, I demonstrated that the IC-based gauge circuit can detect flux residues quickly and cost-effectively. Thus, the non-destructive, repeatable method can be economically applied in industrial environments.

3.5. Based on the surface insulation resistance (SIR) tests and the scanning electron microscopy (SEM-EDS) results, I show that tin migration occurred during the climate test, however, there was no persistent dendrite formation on the surface of the solder mask between the conductive surfaces.

Aims

The aim of this PhD research is i) to examine the effectiveness of CO_2 -snow cleaning, a procedure for reducing ionic residues generated during electronics production. ii) to explore the extent to which current industry cleanliness criteria are applicable in the production of modern automotive products. iii) to propose a measurement method based on surface impedance measurement technique for detecting the amount of flux residues.

The fundamental aspect of the work is to promote the scientific understanding of the problems caused by ionic contaminants and to investigate methods – that can be applied in industry – that help assessing the risk of failure and contribute to its reduction.

Experiments

The experimental work entails four major areas. In the first part, I investigate the efficiency of a CO_2 -snow cleaning system equipped with a bottom infrared heater using image processing, spectroscopy and local ionic contamination-based methods. I investigate the mechanism of the CO_2-snow cleaning system and estimate the kinetic energy of individual particles.

In the following parts of my research, I present a non-destructive and repeatable method for flux detection: I designed a multipurpose test panel for the tests, and I theoretically estimated the capacitance of the interdigital structures (IDS).

Using the method based on alternating current surface impedance (capacitance) measurement, I investigate the change in the electrical properties of interdigital structures under the effect of flux residues over a wide frequency range. With the comparative measurements, I present a cost-effective and fast alternative, which uses a gauge circuit based on an impedance converter IC for capacitance measurement.

Finally, I present a Brownian dynamics simulation method to describe the dynamics of dendrite growth caused by electrochemical migration.

New scientific results, theses

1. I have developed a treatment process that uses bottom infrared heating and multi-cycle scanning of the dry ice-snow jet to ensure that the surface remains above the dew point, thus avoiding condensation. The CO_2-snow blasting process effectively removes residues from OR/L0 type, low-solids, artificially applied, and industrially flux-contaminated immersion tin (ImSn) and electroless Nickel immersion Gold (ENIG) surface finish boards. (Relevant Publications: [C1], [K1])

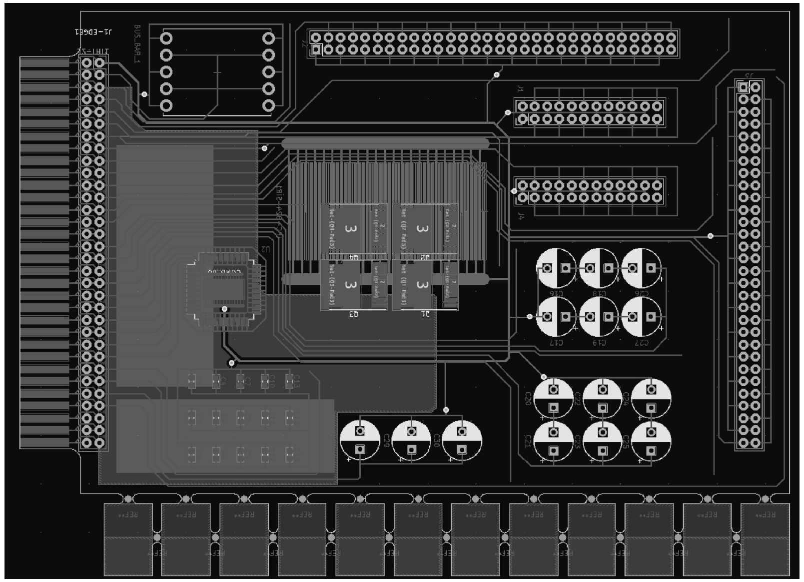
1.1. I determined that the cleaning process, at an absolute mass flow rate of 23.4 kg/h and a scanning speed of 30 mm/s, after 3 cycles, reduces the corrosivity index of ionic contamination from flux applied to the ENIG boards below the limit of 2.08 µA/s used in the automotive industry. Based on infrared spectroscopy (FTIR) and optical tests, the method achieved a cleaning efficiency of over 95% in removing white residues.

1.2. Using the sessile drop method, I showed that dry ice-snow cleaning with an initial mass flow of 23.4 kg/h at a scanning speed of 30 mm/s with 3 repetitions has no effect on the surface free energy of ENIG or ImSn surface finish.

1.3. I have performed measurements of the dry ice-snow removal of activated flux residues applied in an amount of 21 $\mu l/cm^2$ and heat-treated at 140 °C for 1 minute. Based on the results, it can be seen that CO_2-snow cleaning removes the contamination caused by the non-activated flux with an efficiency of over 90% after 3 cycles at an absolute mass flow rate of 16.4 kg/h and a scanning speed of 30 mm/s. Based on optical analysis, I confirmed that the amount of white residue from the activated flux also decreased.

1.4. By measuring the movement of the particles at an absolute mass flow rate of 16.4 kg/h, I estimated the kinetic energy of the dry ice particles ($\sim 3\times 10^{-2}$mJ). I demonstrated that with the above parameters and a scanning speed of 30 mm/s, the white residue from the flux on the surface of the assembled electronic assembly can be removed and the local ionic contamination can be reduced below acceptance limit (2.08 µA/s).

2. I designed a special multi-purpose test vehicle shown in the figure below. (Relevant Publications: **[C2], [C4]**,))



1. Figure: TTC test vehicle design

2.1. The multi-purpose test vehicle can be widely used for both industrial and research purposes for material and cleanliness tests, as well as for solderability and accelerated lifetime tests. The SIR test compatible connection option and the interdigital structures support the implementation of standard and research tests as well. The design of the test panel supports the population of through-hole and surface-mounted components and the testing of their solder joints and their surroundings. It can be manufactured and used with the most popular surface finish – immersion Tin (ImSn), Hot Air Solder Leveling (HASL), Electroless Nickel Immersion Gold (ENIG), Immersion Silver (ImAg) and organic solderability preservative (OSP).

1.1. Based on the multiplate capacitor (MP) and Olthuis (Olt.) theoretical models, I estimated the theoretical values of the capacitance of the interdigital structures of the test vehicle. Furthermore, I determined the nominal square numbers which represent the the electrode geometry of the patterns. The calculated values for the “Nagy IDS” (nominal square number: 1233): $C_N^{(MP)}$=1,4 pF and $C_N^{(Olt.)}$=12,9 pF; for the “Kis IDS” (nominal square number: 720): $C_K^{(MP)}$= 0,8 pF and $C_K^{(Olt.)}$= 1,8 pF.