University of Pannonia
Chemical Engineering and Material Sciences Doctoral School

Flux-minimized Soldering for Automotive Electronic Assemblies

Ph.D. THESIS

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Introduction

In the process of lead-free soldering of electronic assemblies, the use of flux is currently indispensable. Flux plays a role in removing oxides from metal surfaces and promoting wetting of the solder. When using a no-clean flux, in theory, no harmful effects from soldering residues should be expected over the product's intended lifespan. However, practical experience contradicts this, as the use of flux exposes products to reliability risks.

In the automotive electronics industry, failures are largely attributable to product cleanliness. Residual flux on printed circuit boards (PCBs) can cause various types of defects while also compromising the aesthetic appearance of the board. Among other issues, it can promote unwanted solder ball adhesion, hinder the adhesion of coatings or underfill materials, and accelerate PCB corrosion. The most critical issue arises from ionic residues derived from the flux, which can lead to electromigration and the formation of electrical short circuits. With the advancement and miniaturization of the electronic products in the automotive industry, ionic migration can result in catastrophic failures.

Atmospheric pressure plasma treatment is a widely used surface modification technique. It enables microscopic cleaning, surface activation, and coating of various materials such as plastics, metals, textiles, and glass. Plasma treatment can modify only the surface, not the bulk material, and is gentler than chemical surface treatments. Compared to conventional industrial pre-treatment methods, plasma technology offers a more effective and environmentally friendly alternative, which is why it is increasingly being adopted in industrial processes.

In the electronics industry, plasma treatment can be applied as a process step in the manufacturing of base materials, such as printed circuit boards (PCBs), or as a pre-treatment before conformal coating of electronic assemblies. Plasma technology provides the opportunity to create clean and activated metal surfaces while reducing and minimizing the amount of flux used in the soldering process.

The advantages of atmospheric pressure plasma technology include automation, programmability, and the ability to integrate into industrial production lines.

Aims

The aim of the doctoral research is to investigate the effects of fluxes used in the manufacturing of electronic assemblies on product lifespan, as well as to introduce an alternative method for reducing the amount of flux used. Forming gas-based, atmospheric pressure plasma treatment offers an alternative method for preparing pure and activated metal surfaces, which promotes the wetting of the solder and reduces ionic contamination remaining after soldering. This not only improves the efficiency of manufacturing processes but also enhances the reliability and lifespan of the products.

Experiments

The experimental work entails into four major areas.

The first section explores the detrimental effects of flux residues, discussing two failure mechanisms—electrochemical migration and changes in dielectric breakdown strength—along with methods for detecting ionic contamination based on impedance measurements.

The second section presents wettability and solderability test results, demonstrating the soldering-enhancing effect of atmospheric pressure plasma treatment generated from 5% H_2 and 95% N_2 containing forming gas on the soldering surfaces of printed circuit boards. The third section investigates the mechanisms through which plasma treatment exerts its effects, examining the chemical composition and mechanical properties occurring on the treated surface. PCBs with three different types of surface finishes were investigated: immersion tin (ImSn), immersion silver (ImAg), and electroless nickel – immersion gold (ENIG). These surface finishes are widely used in the electronics industry due to their good solderability and reliability. However, all three types are prone to oxidation over time and under certain environmental conditions.

Finally, the fourth section introduces flux-minimized soldering processes for both surface-mount and through-hole technologies, with a particular focus on the material quality of the formed solder joints and their compliance with industry standards.

New scientific results, theses

1. Through the analysis of dendrite growth rates between tin conductor traces spaced 0.5 mm apart using the water drop test, it has been demonstrated that increasing the electric field strength (from 6 to 12 V/mm) results in an average decrease of 56.1% in the mean time to failure (MTTF) (e.g., bridging or short circuit). Furthermore, in the presence of ionic contamination originating from residues of Interflux 2005C no-clean flux, the MTTF decreases by 76.2% on average.
(Relevant publication: **[C1]**)

2. It has been shown that the breakdown voltage of tin-coated FR-4 printed circuit boards decreases with increasing temperature, humidity, and ionic concentration. It was observed that the breakdown voltage of a tin-coated FR-4 PCB contaminated with Interflux 2005C no-clean flux residue is 27% lower than that of a sample with the same material quality without flux contamination. It has been demonstrated that elevated temperature and humidity conditions (40°C, 60% RH) resulted in a lower breakdown voltage for both clean and Interflux 2005C-contaminated surfaces, with reductions of 9.7% and 10.6%, respectively, compared to milder environmental conditions (20°C, 10% RH).
(Relevant publication: **[C2]**)

3. It has been established that for immersion tin (ImSn), immersion silver (ImAg), and electroless nickel-immersion gold (ENIG) surface finishes treated with plasma generated from 5% H_2 and 95% N_2 containing forming gas at atmospheric pressure and a treatment distance of 10 mm, the amount of flux required during soldering can be reduced. This is due to the plasma treatment's ability to enhance wettability and solderability.
(Relevant publications: **[C3**, **K1, K2]**)

3.1. Through contact angle measurements using the sessile drop method, the original and post-plasma-treatment surface free energy of the examined surfaces was determined, employing water and diiodomethane standard solutions. The total surface free energy increased by 104% for immersion tin, 42% for immersion silver, and 88% for electroless nickel-immersion gold surface finishes. Regarding the polar component of surface free energy, increases of 308% for immersion tin, 268% for immersion silver, and 1141% for electroless nickel- immersion gold were observed.

3.2. Wetting curves for the investigated surfaces were determined through solderability tests using molten SAC305 solder heated to 250°C. In the experiments, commercially available Interflux 2005C flux was applied at concentrations of 100%, 50%, 25%, and 12.5%. This dilution series demonstrated that the amount of Interflux 2005C flux required for soldering could be reduced by half for the examined surface finishes when plasma treatment was applied under the specified parameters, without adversely affecting solderability.

4. It has been demonstrated that for immersion tin (ImSn), immersion silver (ImAg), and electroless nickel-immersion gold (ENIG) surface finishes, atmospheric pressure plasma treatment generated from 5% H_2 and 95% N_2 containing formic gas modifies the roughness of the printed circuit board's soldering surface, while having no significant effect on its chemical composition. (Relevant publications: **[C4, K3]**)
   4.1. Based on surface roughness values determined by white light interferometry, it was established that the roughness parameter (R_z) increases following plasma treatment for immersion tin (from 1,611 µm to 1,893 µm), immersion silver (from 1,019 µm to 1,843 µm), and electroless nickel-immersion gold (from 1,358 µm to 1,439 µm) surface finishes. In the case of immersion tin and immersion silver coatings, both the root mean square roughness (S_q) and arithmetic mean roughness (S_a) show an increasing trend, whereas for electroless nickel-gold coatings, a decrease in these values was observed. Analysis of the soldering surfaces before and after plasma treatment using scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS) and laser-induced breakdown spectroscopy (LIBS) revealed no significant changes in the chemical composition.

Scientific publications, presentations and posters for the basis of theses

[C1] Ható, Z; Horváth, B., Guba S., Tóth Zs., **Kocsis E.**, Boda D. and Szalai, I.: Electrochemical migration and dendrite growth between two electrodes: Experiments and Brownian dynamics simulations International Journal of Heat and Mass Transfer, 126108, ISSN 0017-9310, Volume 234, (2024)
https://doi.org/10.1016/j.ijheatmasstransfer.2024.126108

[C2] Guba, S., Horváth, B., Gugolya, Z., **Kocsis, E.** and Szalai I.: Dielectric breakdown characteristics of flux-contaminated printed circuit boards in different environmental conditions, Heliyon 11 (2025) e42324
https://doi.org/10.1016/j.heliyon.2025.e42324

[C3] **Kocsis, E.**; Lukács, A. and Szalai, I.: Impact of plasma treatment on solderability of printed circuit boards, IOP Conference Series: Materials Science and Engineering: 1246 (2022) 012013
doi:10.1088/1757-899X/1246/1/012013

[C4] **Kocsis E.;** Lukács, A. and Szalai, I.: Investigation of Atmospheric Pressure Plasma Treatment on PCB Surface Finishes, IEEE Transactions on Plasma Science, vol. 52, no. 11, pp. 5345-5349, Nov. 2024
doi: 10.1109/TPS.2024.3507074

[K1] **Kocsis, E.;** Lukács, A. és Szalai, I.: Plazmakezelés hatásvizsgálata nyomtatott áramköri panelek forraszthatóságára, XIII. Országos Anyagtudományi Konferencia, Balatonkenese, October 10-12, 2021

[K2] **Kocsis, E.;** Lukács, A. és Szalai, I.: Plazmakezelés hatása elektronikai szerelvények forraszthatóságára, ENELKO 2022 - XXIII. Nemzetközi Energetika-Elektrotechnika Konferencia, SzámOkt 2022 - XXXII. Nemzetközi Számítástechnika és Oktatás Konferencia, Erdélyi Magyar Műszaki Tudományos Társaság (EMT), (2022) pp. 25-29., 4 p., ENELKO, Marosvásárhely, Románia, October 13-16, 2022

[K3] **Kocsis, E.;** Lukács, A. és Szalai, I.: Investigation of Atmospheric Pressure Plasma Treatment on PCB Surface Finishes, Conference on MACRO meets NANO in Measurement for Diagnostics, Optimization and Control, Delft, Netherlands, September 21-22, 2023

Other scientific publications, presentations

1. Tóth, Zs; **Kocsis E.**, Szalai, I. and Lukács, A.: "No-Clean" Flux Residues Detection With Impedance Measurements, IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 14, no. 4, pp. 729-734, (2024), https://doi.org/10.1109/TCPMT.2024.3382098
2. **Kocsis, E.;** Lukács, A. és Szalai, I.: Plazmakezelés nyomtatott áramköri panelek forraszthatóságának javítására, PhD hallgatók anyagtudományi napja XXI., Veszprém, 2021. november 8.
3. **Kocsis, E.;** Lukács, A. és Szalai, I.: Plazmakezelés tisztítási hatékonyságának vizsgálata forrasztott elektronikai termékeken, PhD hallgatók anyagtudományi napja XXII., Veszprém, 2021. november 14.