Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira,
Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria

Published by Research Publishing, Singapore.
doi: 10.3850/ESREL2026061419_esrel26-p26445-cd

Realization of a Circular Economy for Solder Pastes: Development of a Multi-Stage Separation and Recovery Process

Philipp Heß[1], Marc Nierstenhöfer[2], Nils Kopp[3], Rüdiger Knofe[4], Tsvetanka Alyova-Pfropper[5],
Roland Goertz[2] and Stefan Bracke[1]

[1] *Chair of Reliability Engineering and Risk Analytics, University of Wuppertal, Wuppertal, Germany.*
E-mail: hess@uni-wuppertal.de, bracke@uni-wuppertal.de

[2] *Chair of Chemical Safety and Fire Defence, University of Wuppertal, Wuppertal, Germany.*
E-mail: nierstenhoefer@uni-wuppertal.de, goertz@uni-wuppertal.de

[3] *Tamura Elsold GmbH, Ilsenburg, Germany*

[4] *Siemens AG, Berlin, Germany*

[5] *Hellmann Process Management GmbH & Co. KG, Osnabrück, Germany*

The disposal of solder paste waste poses significant environmental and economic challenges for the electronics industry. Due to their limited shelf life, large volumes of solder pastes are incinerated after use or upon expiration, resulting in the permanent loss of valuable raw materials. To address the associated environmental and economic challenges, this work presents a purification and recycling approach for expired solder pastes within the framework of the Zero Waste Paste (ZWP) project. The focus lies on the non-destructive separation of the metallic solder powder from fluxes, additives, and other organic constituents while preserving particle morphology and material quality for reuse. Several solvent-based extraction procedures using non-aggressive organic solvents were systematically investigated and optimized for yield, purity, and processability. The most promising methods achieved recovery rates of up to 86.8 wt% of clean solder metal powder. Comprehensive material characterization was performed using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), viscosity measurements, and thermogravimetric analysis (TGA), confirming high purity, intact spherical particle morphology, and minimal residual organic contamination. Furthermore, solder pastes containing recycled solder powder were produced and subjected to static and dynamic qualification tests, demonstrating performance comparable to conventional reference pastes. The results indicate that the proposed purification approach enables the effective recycling of solder paste waste and represents a viable step toward a circular economy in electronics manufacturing. Future work will address scalability, process automation, and validation under industrial production conditions.

Keywords: Reflow soldering process, Solder paste waste, Solder paste recycling, Solder paste purification, Circular economy, Zero Waste Paste, Reliability, Lead-free solder alloys, SEM/EDX material characterization, Thermogravimetric analysis (TGA), Recycled solder powder reliability, Solder paste qualification

1. Introduction

In the industrial mass production of printed circuit boards (PCBs), reflow soldering with solder paste is the dominant joining process, especially for surface-mounted components (Figure 1). Reflow soldering is a standardized surface mount technology that uses solder paste and flux to solder surface mount devices (SMD) onto printed circuit boards prior to placement (Illés et al., 2020). Thermal energy is introduced during the process, following a defined temperature-time profile. This causes the solder paste to melt and form electrical and mechanical joints. Typically, this is done using convection, condensation, or jet-printing techniques. With maximum process temperatures of up to 250 °C, reflow soldering is classified as a soft soldering method.

The quality and composition of solder paste significantly influence the mechanical stability, electrical functionality, and long-term reliability of solder joints. Solder pastes are primarily composed of a metallic solder alloy and a flux,

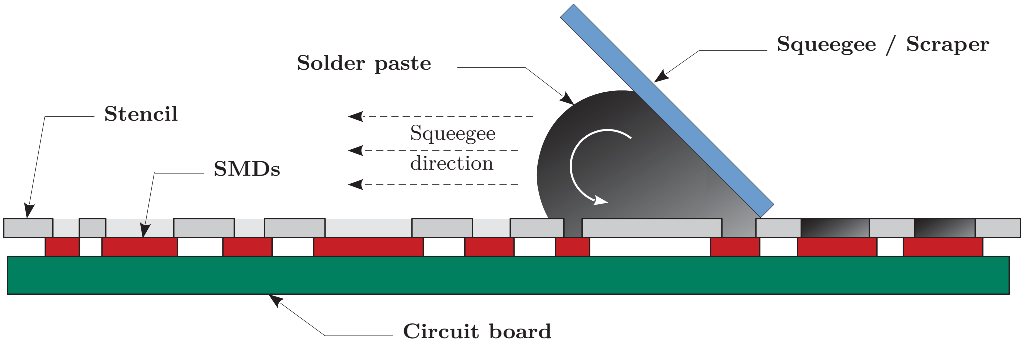

Fig. 1. Application of solder paste to a printed circuit board through a stencil (Heß et al., 2025)

with additives included to adjust specific properties as needed. The relevant standards, such as IPC J-STD-005 (IPC International, 2024) and DIN EN 61190-1-2 (DIN German Institute for Standardization, 2014), define the particle size, sphericity, and purity of the solder powder to ensure reliable wettability. Solder metal content accounts for 85–90% of total mass, significantly determining solder joint properties. Today, lead-free SnAgCu alloys, such as SAC305 or SAC387, are predominantly used.

Flux is used to remove oxide layers and protect against reoxidation during the reflow process. It consists mainly of resins, activators, and solvents. Depending on their chemical composition, fluxes are classified as resin, organic, or inorganic types according to DIN EN ISO 9454-1 (DIN German Institute for Standardization, 2016). Additives, such as thixotropic agents and solvents, regulate the viscosity of solder paste, which is crucial for stencil printing and wetting. Solder pastes have a limited shelf life of about six months when stored in a cool place due to aging processes that lead to phase separation and changes in rheological properties. Therefore, solder pastes are offered in comparatively small packaging units to minimize aging effects and material losses.

Numerous concepts and methodologies have been devised to mitigate pollutants and facilitate the reuse and recovery of solder paste waste, with a particular emphasis on environmental protection, occupational health, and regulatory compliance (Prasad et al., 2021). The relevant legal framework conditions include adherence to environmental standards and directives, such as the RoHS directive (Das europäische Parlament und der Rat der europäischen Union, 2024). Beyond general strategies for electronic waste recycling, several specific approaches for solder paste recycling have been identified, encompassing mechanical, chemical, and thermal separation processes (Hwang, 1992). Comparative studies on the soldering performance of recycled versus conventional solder pastes have also been reported (Tanaka et al., 2012). Furthermore, research has been conducted on the reduction of hazardous substances and the minimization of lead and flux emissions during recycling and processing (Chang et al., 2022) and physical separation processes (Stannol GmbH & Co. KG, 2024).

Containers of solder paste produced in this process are considered hazardous waste and are nevertheless incinerated as hazardous waste. This results in environmental pollution and the loss of valuable raw materials. Against this backdrop, the Zero Waste Paste (ZWP) research project aims to fully recycle solder paste waste in accordance with the principles of a circular economy (Heß et al., 2025). In addition to recovering the solder metal, the flux and container materials will be collected and recycled as well. To this end, the project is developing logistical, legal, and technical solutions that will enable the efficient, automated, and sorted return of raw materials to the production cycle.

From a safety and reliability perspective, the reuse of recycled solder materials poses potential risks related to residual contamination, altered rheological behavior, and particle morphology changes, which may directly affect solder joint integrity and long-term reliability.

2. Purification of solder paste

Designing a suitable procedure for the purification of solder paste was quite challenging due to the limitations of the properties of the solder metal that had to be maintained for subsequent reuse. The desired process had to:

(i) keep the spherical particles of solder metal undissolved and the morphology unchanged.
(ii) separate the flux and additives from metal compounds.
(iii) contain only safe or easily manageable chemical solvents due to safety standards for the work environment.
(iv) be upscalable for industrial purposes.

The process requirements were defined to explicitly mitigate reliability- and safety-related risks, such as mechanically induced particle deformation, chemically driven surface degradation, and uncontrolled variability during industrial scale-up. These limitations resulted in a significant decrease of possible extraction solvents and mechanical treatments which could be considered in this recycling process. It is widely known that alkaline or acidic solutions can attack metallic surfaces by destroying their spherical particle morphology, making the result unsuitable for further recycling processes.

Even applying small mechanical forces during the transfer of the raw product from the fine glass frit to new containers via common laboratory dishes led to minor contamination occurred from borosilicate glass particles in the frit material along with deformation of some spherical metal particles (Figure2).

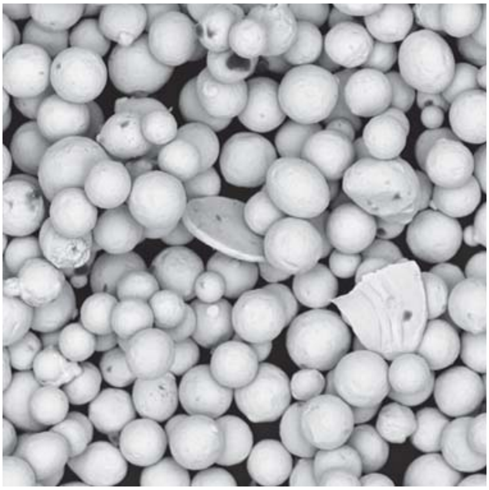

Fig. 2. Scanning electron microscope images of a purified solder paste: Deformed or destroyed solder balls

Therefore, non-aggressive solvents or mixtures were used for extraction, avoiding changes in the particle morphology. In addition, only mild stirring methods such as ultrasonic treatment in this case were applied to carefully suspend the solder paste with the extraction solvent. The use of non-aggressive and industrially manageable solvents further reduces occupational safety risks and supports process stability, which is essential for reliable implementation in an industrial manufacturing environment.

In initial lab scale experiments, small amounts of expired solder paste were extracted using polar organic solvents belonging to the ester (Solvent A) and sulfoxide (Solvent B) classes (see Table 1), with the samples subjected to repeated sonication in an ultrasonic bath (Figure 3). For patent purposes, only the classes of chemical compounds are specified. Particularly, anorganic and organic sulfoxides are known to be an advantageous solvent for dissolving a variety of chemical compounds. This solvent removed unwanted flux agents and additives such as resins or stabilizers successively, which were separated by subsequent filtration without attacking the metal particles, keeping their shape and morphology untouched.

Different procedures were tested in order to optimize the extraction process with respect to yield, purity and practicability. The selection of solvents was based on their ability to dissolve organic flux components while maintaining the integrity of the metallic particles. Highly polar solvents such as Solvent A and Solvent B were

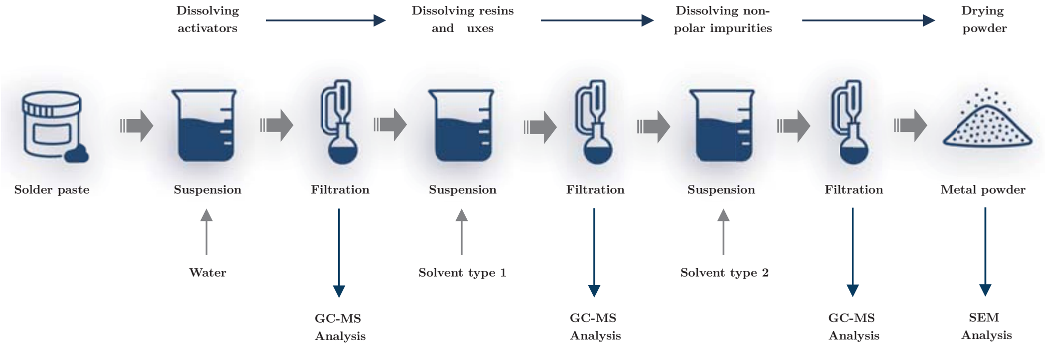

Fig. 3. Simple illustration of a non-destructive recycling process for the separation of the solder metal from flux, additives and other organic constituents.

chosen due to their excellent solvation properties for organic compounds, while ethanol served as a final washing step to remove residuals solvents, residues that were not separated during the previous extraction step and facilitate drying. The procedures differed in the choice of extraction solvents, the sequence of solvent apllications and the use of solvent mixtures. The used solvents for each procedure are summarized in Table 1 and the detailed experimental protocols are describe in Section 3.

Table 1. Used solvents for various extraction steps for each procedure

Procedure	Step 1	Step 2	Step 3
1a	Solvent A	EtOH	-
1b	Solvent A/EtOH	-*	-
1c	Solvent A/EtOH	-*	-
2a	Solvent B	-*	-
2b	Solvent B	EtOH	-
2c	Solvent B/EtOH	-*	-
2d	Solvent B	EtOH	Xylene*

* To ensure complete separation of the extraction agent and better drying of the final product, the residue was washed with small amounts of ethanol in the final step.

The best results were obtained using highly polar organic solvents such as Solvent A or Solvent B in combination with technical ethanol. In these cases, a fine gray-silver metallic powder suitable for reuse could be recovered as determined by SEM and EDX analysis (Section 4). Further attempts by using different organic solvents like dichloromethane, acetonitrile, propan-2-ol, hexane and chloroform led to sticky pastes as the final result and were therefore rejected. Almost all promising methods ended with ethanol extraction as the final purification step to ensure the removal of residual higher-boiling solvents A and B and better drying due to its high vapor pressure.

3. Purification procedures

Separation and purification of the solder metal were performed by extracting the solder paste with various solvents in order to remove flux, additives and other organic constituents. Every extraction step was repeated three times consecutively. Note that only the most promising procedures are listed below as indicated by subsequent SEM analysis.

The solvents CH_3CN (HPLC grade, Fisher Chemical), CH_2Cl_2 (Fisher Chemical), C_6H_{14} (95%, VWR Chemicals), EtOH (technical grade, 99%, Julius Hoesch), $CHCl_3$ (VWR), C_3H_8O (technical grade, Julius Hoesch), and xylene (mixture of isomers, Carlo Erba) used for extraction steps were commercial available and used without any further purification. Laboratory-scale experiments were conducted using a solder paste with the following composition: Sn (96.5 wt%), Ag (3.0 wt%) and Cu (0.5 wt%), type 25-45 µm corresponding to a total solder metal content of 88.5 wt%.

For stirring purposes, an ALLPAX PTIC-3-ES ultrasonicator was used for 5 min at room temperature for each extraction step. Fine glass frits with G4 grade (ROBU, H11) were used for filtration processes to ensure the collection of metal particles with sizes >16 mm. Drying of the final products was achieved by using a KNF Labopart (N810.3 FT.18) membrane pump.

Procedure 1a: A 5.00 g portion of expired solder paste was suspended in 20 mL of solvent A and stirred for 5 min in an ultrasonic bath at room temperature. The suspension was filtered and dried in vacuo for 5 min. The residue was transferred using small amounts of Solvent A and the extraction was repeated twice. The extraction was then repeated three times with 20 mL of ethanol each time following the described method and the product was dried in vacuo for 30 min. This yielded 4.16 g (83.2% w/w) of a light gray-silver metallic powder.

Procedure 1b: A 5.00 g portion of expired solder paste was suspended in 20 mL of solvent A/EtOH (50/50, v/v) and stirred for 5 min in an ultrasonic bath at room temperature. The suspension was filtered and dried in vacuo for 5 min. The residue was transferred using small amounts of the extraction solvent and the procedure was repeated twice. The residue was carefully suspended in 10 mL of EtOH, filtered and dried in vacuo for 30 min. This yielded 4.31 g (86.2% w/w) of a light gray-silver metallic powder.

Procedure 1c: A 5.00 g portion of expired solder paste was suspended in 20 mL of solvent A/EtOH (60/40, v/v) and stirred for 5 min in an ultrasonic bath at room temperature. The suspension was filtered and dried in vacuo for 5 min. The sticky residue was washed with 2 ml of ethanol and transferred using small amounts of the extraction solvent and the procedure was repeated twice. The residue was carefully suspended in 10 ml of EtOH, filtered and dried in vacuo for 30 min. This yielded 4.34 g (86.8% w/w) of a light gray-silver metallic powder.

Procedure 2a: A 5.00 g portion of expired solder paste was suspended in 20 mL of solvent B and stirred for 5 min in an ultrasonic bath at room temperature. The suspension was filtered and dried in vacuo for 5 min. The sticky residue was washed with 3 mL of ethanol and transferred using small amounts of solvent B and the procedure was repeated twice. The residue was carefully suspended twice in 2 ml of EtOH, filtered and dried in vacuo for 30 min. This yielded 4.31 g (86.2% w/w) of a light gray-silver metallic powder.

Procedure 2b: A 2.10 g portion of the product obtained from procedure 2a was suspended in 20 mL of EtOH and stirred for 5 min in an ultrasonic bath at room temperature. The suspension was filtered and dried in vacuo for 5 min. This was repeated twice more. After drying in vacuo for 30 min, 2.08 g of a light gray-silver metallic powder was obtained.

Procedure 2c: A 5.00 g portion of expired solder paste was suspended in 20 mL of solvent B/EtOH (50/50, v/v) and stirred for 5 min in an ultrasonic bath at room temperature. The suspension was filtered and dried in vacuo for 5 min. The residue was transferred using small amounts of the extraction solvent and the procedure was repeated twice. The residue was carefully suspended in 10 mL of EtOH, filtered and dried in vacuo for 30 min. This yielded 4.32 g (86.4% w/w) of a light gray-silver metallic powder.

Procedure 2d: A 1.00 g portion of the product obtained from procedure 2b was suspended in 5 mL of xylene and stirred for 5 min in an ultrasonic bath at room temperature. The suspension was filtered and dried in vacuo for 5 min. This was repeated twice more. After drying in vacuo for 30 min, 0.99 g of a light gray-silver metallic powder was obtained.

4. Analysis of purified solder metal

Separated and cleaned solder pastes and solder metal powders were analysed using various methods to validate the purification performance and suitability of the methods and solvents used.

SEM / EDX analysis: The results of the REM / SEM analysis of the separated and cleaned solder metal powders indicate that the purifica-

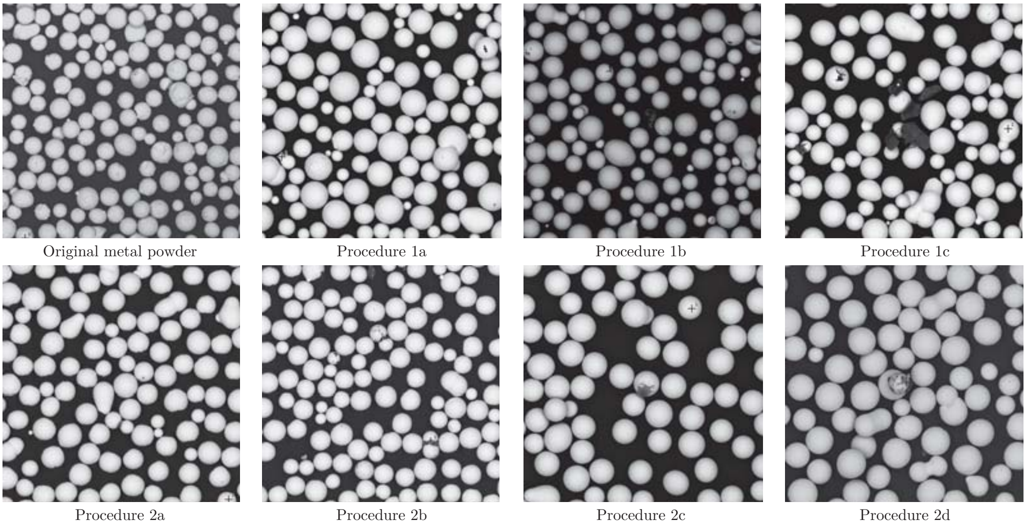
Original metal powder
Procedure 1a
Procedure 1b
Procedure 1c
Procedure 2a
Procedure 2b
Procedure 2c
Procedure 2d

Fig. 4. Scanning electron microscope images of original metal powder and powder of different purified solder pastes

tion procedures and solvents employed resulted in high purification rates compared to the reference powder (Figure 4). All samples exhibited a high degree of powder purity, with minimal levels of adhesions or residues from organic components (flux, resins, etc.). Additionally, the solder balls exhibited no deformation resulting from the processes and solvents employed in conjunction with a transfer process devoid of mechanical influence. The preserved spherical morphology and absence of surface residues are particularly relevant for preventing reliability-critical failure mechanisms such as insufficient wetting, void formation, and increased electromigration susceptibility.

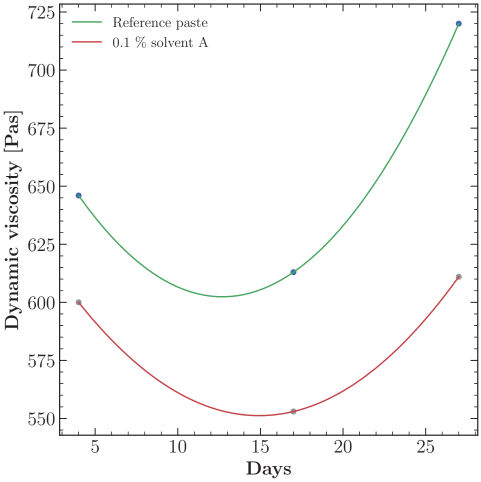

Fig. 5. Analysis of the influence of solvent A on the solder paste viscosity: Consistent viscosity stability over time when adding 0.1% of solvent A.

Viscosity analysis: In order to investigate the influence of potential residues of the most promising solvent with respect to hazards and purification efficiency on the recovered powder and the pastes prepared from it, a solder paste (TLF-204-171A) was doped with a small amount of solvent B (ca. 0.1%), and subsequently, a basic characterization was performed (Figure 5).

The wetting behavior and solder ball test remained unchanged and excellent, as did the surface insulation resistance during an electromigration test (85 °C/ 85% RH / ca. 250 h / IPC -24) with $>$1013 Ω. The viscosity was, as expected due to the addition of liquid, slightly reduced. However, it remained stable during storage to the same extent as the reference paste. Overall, no indication could be found that a potentially remaining solvent contamination with solvent A poses a risk for paste production.

Thermogravimetric analysis: In order to develop a method for the characterization and quantitative determination of the residues of flux and possible solvent remaining after the purification process, thermogravimetric analyses were performed. Original powder as a reference, a solder paste washed with solvent A, and powder doped with solvent A were investigated (Figure 6).

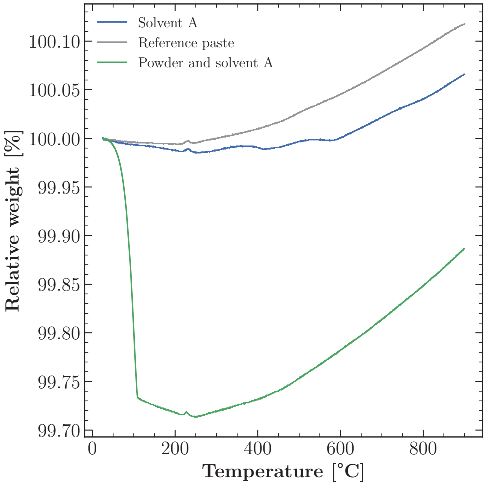

Fig. 6. Thermogravimetric analysis of reference paste, washed solder paste, and mixed solder powder: Relative weight [%] over temperature [°C] at a heating rate of 10 K/min.

All three samples show a peak at approximately 219 °C, which corresponds to the melting temperature of the solder alloy. Above this temperature, a weight increase occurs, which can be attributed to oxidation despite the protective gas atmosphere. The powder sample doped with solvent A shows a rapid weight loss up to just above 100 °C, which can be attributed to evaporation of solvent A. This does not occur significantly for the solder paste sample washed with Solvent A, indicating that no or very low residues of solvent A remain. However, between 250 °C and 600 °C, two peaks are visible, which indicate evaporation of flux residues. An examination of the difference between the washed paste and the reference powder yields a calculated difference of 0.035% in total, with an initial flux content of approximately 11% and a target for residual contamination of 0.1%, which was thus achieved on the laboratory scale.

5. Analysis of solder paste with recycled solder metal powder

Following the successful validation of the purification process, a solder paste containing recycled solder metal powder (based on solvent A) was produced on a laboratory scale for the purpose of analyzing the general suitability of the newly produced solder paste. The solder pastes subjected to analysis were TEG Solder Paste TLF204-NHLV, containing 25% recycled (purified) solder metal powder, and TEG Solder Paste TLF204-NHLV, devoid of recycled solder powder (reference). The evaluation of both solder pastes was conducted as part of a comprehensive qualification process, encompassing both static and dynamic assessments.

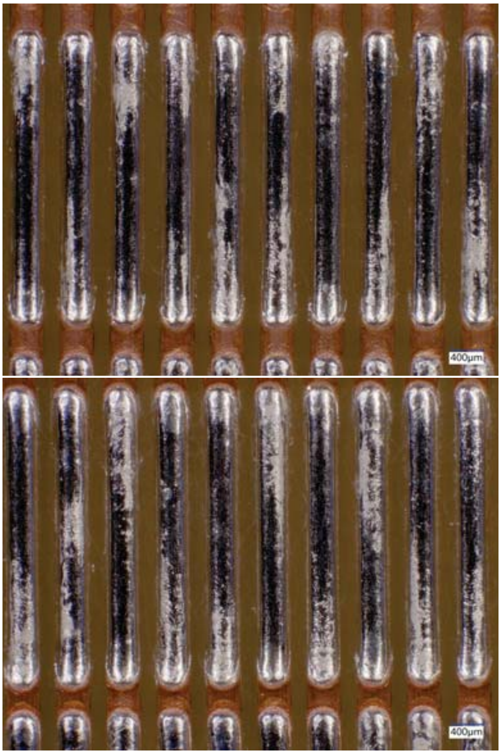

Fig. 7. Wetting tests: Solder paste 228-11C (Top) and solder paste with 25% recycled solder powder 228-6A (Bottom)

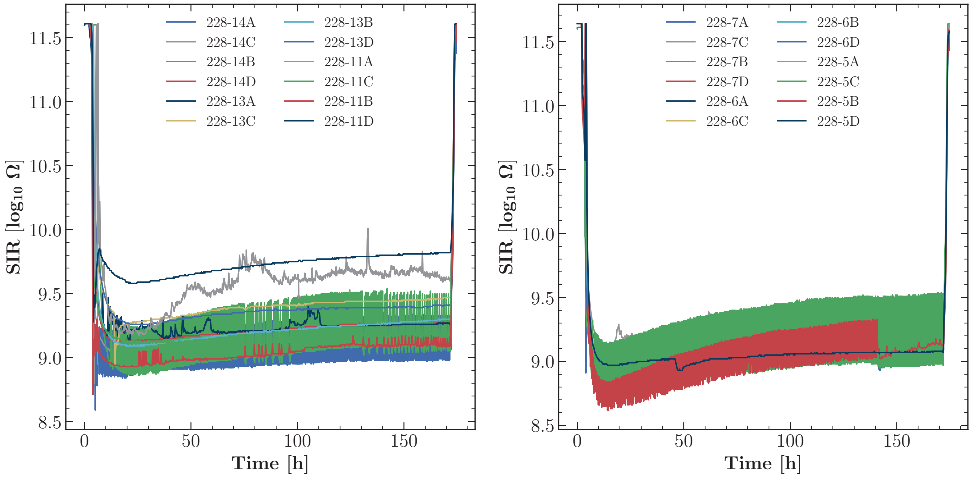

Fig. 8. SIR measurements: Soldering profile P3 under normal atmosphere of reference solder paste 228-11C (Left) and solder paste with 25% recycled solder powder 228-6A (Right)

As part of the static qualifications, melting and wetting tests (Figure 7) were carried out on copper and ceramic specimens, in addition to a surface insulation resistance (SIR) measurement (Figure 8). To this end, two distinct soldering profiles with two different soldering atmospheres were examined. The analyses did not reveal any significant differences between the two solder pastes. It is noteworthy that both the solder pastes containing recycled solder powder and the reference solder paste fully meet the defined quality criteria.

As part of the dynamic partial evaluation, various geometries were printed on test circuit boards, and the release behavior (from the stencil) of the two solder pastes was compared. This resulted in moderately improved outcomes for the recycled solder paste compared to the standard product, which may be due to the lower viscosity of the recycled solder paste. The preliminary exploratory test demonstrated the general usability of the solder paste with recycled content (purified solder powder), despite the presence of residual organic matter.

6. Summary and outlook

The primary objective of this work was the development of a purification procedure for the recycling of (expired) solder paste, focusing on the separation of the metallic component from flux and additives. Various extraction procedures using organic solvents were investigated. The best results were obtained with highly polar solvents A and B in combination with ethanol, yielding clean metallic powders with recovery rates of up to 86.8% (w/w). The recovered materials were analyzed by SEM / EDX, viscosity analysis, and thermogravimetric analysis, confirming that the spherical particle morphology remained intact and that possible residual flux contamination has no significant influence on the properties of the solder paste. First attempts of solder pastes containing recycled metal were subsequently prepared and characterized, demonstrating their general suitability for application. Overall, the results demonstrate that the proposed recycling process enables material recovery without introducing additional safety or reliability risks, thereby supporting the integration of circular economy approaches into electronics manufacturing.

Despite these promising laboratory-scale results, several aspects require further investigation. First, additional solder pastes containing varying fractions of recycled metal need to be prepared and tested under realistic application conditions. Second, the scalability of the procedure must be validated by processing larger quantities to assess economic feasibility. Third, the transferability to other paste types, including different alloy compositions and flux formulations, needs to be investigated to determine the general applicability of this approach. Fourth, the design of a prototypical automated system for continuous cleaning and recycling represents an important step toward industrial implementation. Finally, the development of analytical strategies for quality assessment, including rapid screening methods and standardized acceptance criteria is essential to ensure consistent product quality and facilitate integration into existing production processes.

Acknowledgement

The authors would like to thank the project sponsor the German Federal Ministry for Economic Affairs and Climate Action for funding and supporting the Zero Waste Paste project: Realization of a circular economy through the development of an energy-efficient and automated process and system prototype for the gentle recovery of raw materials from solder paste waste (administrated by the project sponsor Jülich, Funding codes: 03EI5021A, 03EI5021B, 03EI5021C and 03EI5021D).

References

Chang, M. S., M. A. A. M. Salleh, D. S. C. Halin, and N. Z. M. Mokhtar (2022). Tin Whiskers Growth in Electronic Assemblies. In M. A. A. M. Salleh, M. S. Abdul Aziz, A. Jalar, and M. I. Izwan Ramli (Eds.), *Recent Progress in Lead-Free Solder Technology*, pp. 311–328. Cham: Springer International Publishing.

Das europäische Parlament und der Rat der europäischen Union (2024). Richtlinie 2011/65/EU des europäischen Parlaments und des Rates vom 8. Juni 2011 zur Beschränkung der Verwendug bestimmter gefährlicher Stoffe in Elektro- und Elektronikgeräten.

DIN German Institute for Standardization (2014). *DIN EN 61190-1-2: Attachment Materials for Electronic Assembly - Part 1-2: Requirements for Soldering Pastes for High-Quality Interconnects in Electronics Assembly (IEC 61190-1-2:2014); German Version EN 61190-1-2:2014*. Berlin, Germany.

DIN German Institute for Standardization (2016). Soft soldering fluxes - Classification and requirements - Part 1: Classification, labelling and packaging (ISO 9454-1:2016); German version EN ISO 9454-1:2016.

Heß, P., N. Kopp, R. Knofe, T. Alyova-Pfropper, and S. Bracke (2025). The Zero Waste Paste Project: Development of an Energy-Efficient and Automated Process for the Gentle Recovery of Raw Materials from Solder Paste Waste. In *35th European Safety and Reliability Conference (ESREL 2025) and the 33rd Society for Risk Analysis Europe Conference (SRA-E 2025)*, Singapore EXPO, Singapore, pp. 3007–3014. Research Publishing Services.

Hwang, J. S. (1992). *Solder Paste in Electronics Packaging: Technology and Applications in Surface Mount, Hybrid Circuits, and Component Assembly*. New York: Van Nostrand Reinhold.

Illés, B., A. Géczy, and O. Krammer (2020). *Reflow Soldering: Apparatus and Heat Transfer Processes*. Amsterdam, Netherlands: Elsevier.

IPC International (2024). *IPC-J-STD-005B: Requirements for Solder Pastes*.

Prasad, M. N. V., M. Vithanage, and A. Borthakur (Eds.) (2021). *Handbook of Electronic Waste Management: International Best Practices and Case Studies* ([Enhanced Credo edition] ed.). Amsterdam, Boston, Massachusetts: Elsevier : Butterworth-Heinemann, Credo Reference.

Stannol GmbH & Co. KG (2024). REACT-EU: Grüne Transformation. https://metallpasten-recycling.de/react-projekt/ergebnisse.

Tanaka, T., Y. Shimada, H. Takahashi, and K. Tohji (2012). Effective and Low Energy Recycling Method for Solder Paste. *Journal of The Japan Institute of Electronics Packaging 15*(3), 164–168.