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The Zero Waste Paste project: Development of an energy-efficient and automated process for the gentle recovery of raw materials from solder paste waste

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During the assembly, solder pastes are employed in the mass production of printed circuit boards. However, they possess a restricted shelf life. The solder paste containers and the residues of the (expired) solder paste are classified as hazardous waste. There is no automated process to remove the solder paste from the containers without leaving any residue, thus allowing for the targeted recycling of all components. Instead, the containers are incinerated as hazardous waste, which results in inefficient recovery and high environmental pollution. This paper outlines a research project that aims to develop an environmentally friendly circular economy, with the objective of recovering or recycling all components of solder paste waste. The initial phase of the project will entail the development of a process and construction of an associated system prototype to facilitate the automated, efficient, and gentle recovery of raw materials from solder paste components (solder metal and flux) and the container material (polypropylene and polyethylene). Concurrently, a logistics system is being developed to ensure the efficient collection and pre-sorting of containers according to the paste components they contain. The incorporation of recovered components into the manufacturing process of new solder paste is also being considered, with the development of new recycling options to realize the implementation of a circular economy with the objective of zero waste. The design of the washing process represents the initial stage of the concept phase and serves as a fundamental element. Cleaning and separation tests were conducted to evaluate the suitability of various processes and solvents. The tests encompass a range of technical processes, solvents and liquid nitrogen. The objective is to assess the repeatability and reliability of the cleaning and separation processes, while minimizing the impact on the environment and human health. The initial findings of the project's analyses are presented and discussed in detail.

Keywords: Soldering, Reflow soldering process, Solder paste waste, Circular economy, Zero waste, Recycling, Reliability.

1. Introduction

Printed circuit boards (PCBs) constitute the fundamental basis of modern electronics and play a central role in almost all areas of daily life. They enable the integration and connection of complex electronic components and are therefore indispensable for technological progress, economic development and social change. Electronic devices based on printed circuit boards permeate our everyday lives. From smartphones and computers to household appliances, vehicles and medical devices – these technologies would be unthinkable without PCBs. They are proving to be indispensable in the realms of communication, mobility and healthcare, in particular. They facilitate the advancement of intelligent vehicles, life-saving medical implants, and energy-efficient systems in industry and in the supply of renewable energies. The miniaturisation and multifunctionality of modern PCBs has also facilitated the emergence of entirely novel fields of application, including the Internet of Things (IoT) and Artificial Intelligence (AI). These developments foster innovation and enhance efficiency across a range of sectors, including business, science and technology. Concurrently, they represent a pivotal enabler of digitalisation and automation, which are addressing numerous social challenges, including climate change and resource conservation.

During the assembly in the mass production of PCBs, reflow soldering, in which solder is used in the form of paste, is employed for approximately 90% of the assembly of electronic components like surface mount devices (SMDs). This is due to the increasing complexity of PCBs, which are becoming increasingly miniaturized. The solder paste containers are classified as hazardous waste and are therefore difficult to dispose. They are usually incinerated as hazardous waste, which is harmful to the environment and results in the inefficient recovery of the solder metal.

The objective of the Zero Waste Paste (ZWP) research project is to facilitate the transition to a circular economy by recycling solder paste waste. This process aims to recover not only the solder metal, ideally directly as a powder, but also the flux and the container material. The project's realization entails the development of a logistics system that considers the utilization of short transport routes and the implementation of uniform, transparent, and traceable labelling in accordance with waste legislation. This serves as the foundation for the effective and unmixed recovery of the raw materials. The automated, efficient and gentle recovery of raw materials from the three components (solder metal / powder, flux and container material) is to be carried out using a prototype system that is currently under development. One of the project's primary objectives is to recycle the individual components. The aim is to return the raw materials to the manufacturer of solder paste, thereby establishing a raw material cycle that does not currently exist. In line with the ZWP goal, the intention is to incorporate not only the solder metal but also the flux and the container material into the production of new solder paste or other solder products.

2. State of the art in science and technology

The following section presents an overview of the current state of the art of reflow soldering process science and technology, with a particular focus on the solder paste(s) under consideration. In addition to the solder paste itself, which consists of solder metal (tin-based alloys) and flux (organic substances), the materials to be recycled also include the solder paste container, which is made of plastic (usually polypropylene and polyethylene). Additionally, it outlines the existing utilization and recycling options, as well as the pertinent legal framework conditions.

2.1. *Reflow soldering*

Reflow soldering represents a standardized process or surface mount technology (SMT) for the soldering of SMDs, including resistors, diodes, transistors, coils, capacitors and integrated circuits (ICs), onto PCBs. Firstly, solder paste and flux are applied to the PCB with a squeegee or scraper through a stencil (see Figure 1) before the intended SMDs are placed on the PCB (Illés et al., 2020). The established reflow soldering processes include convection and condensation reflow soldering, as well as jet printing, in which the solder paste is applied using a nozzle head. During the reflow soldering process, thermal energy is then introduced into the pre-assembled module via a precisely defined temperature-time profile. The solder paste is heated above the melting temperature, causing it to melt and solder the SMDs to the PCB. The maximum temperature applied during reflow soldering is 250 °C, which is the reason why this process is classified as a soft soldering technique.

2.2. *Solder paste*

The quality and properties of the solder paste have a significant influence on the mechanical stability, electrical functionality and reliability of the manufactured connections. The composition of the solder paste is typically made up of two main components: the solder alloy and the flux. In addition, additives can be added to improve specific properties. The particle sizes in the solder pastes vary depending on the type of paste, as defined in the IPC J-STD-005 standard (IPC International, 2024) or DIN-EN 61190-1-2:2004 standard (DIN German Institute for Standardization, 2014). Furthermore, the standard sets forth additional stipulations pertaining to sphericity and purity (of particles, oxides etc.) with the objective

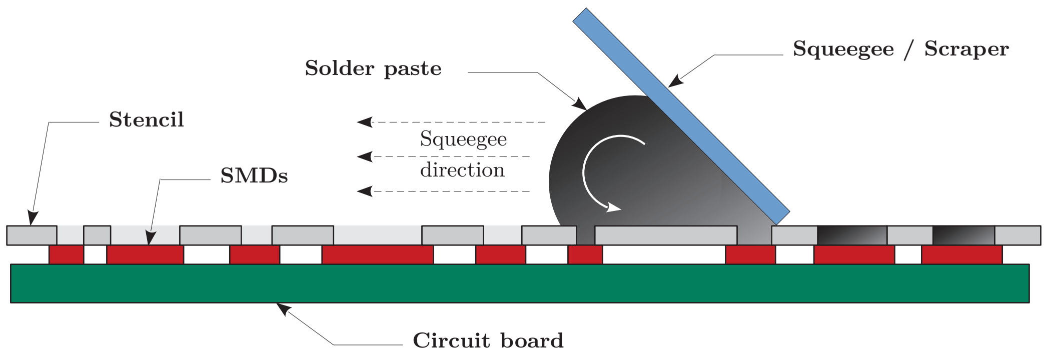

Fig. 1. Application of solder paste to a printed circuit board through a stencil

of guaranteeing solderability.

The solder alloy or solder metal powder constitutes the metallic component of the solder paste, comprising approximately 85% to 90% of the total mass, and is responsible for determining the mechanical and electrical properties of the solder joint. The most commonly utilized solder alloys comprise tin (Sn), lead (Pb), silver (Ag), copper (Cu), bismuth (Bi) and antimony (Sb). Since the introduction of the Restriction of Hazardous Substances (RoHS) directive, the use of alloys containing lead has been subject to significant restrictions. The most commonly utilized lead-free alloys are SnAgCu (also designated SAC), comprising tin, silver and copper. The most prevalent lead-free compositions are SAC305 (96.5% Sn, 3.0% Ag, 0.5% Cu) and SAC387 (95.5% Sn, 3.8% Ag, 0.7% Cu).

The flux is employed to remove oxide layers from the surfaces of metals and to safeguard them from further oxidation during the reflow process. It is primarily composed of resins (e.g., colophony), activators, and solvents. The activators play a pivotal role in reducing the oxide layers and initiating chemical reactions that ensure a clean metal surface for wetting by the solder alloy. Fluxes for soft soldering are classified into three categories according to the standards set forth in DIN EN ISO 9454-1: resin, organic, and inorganic fluxes.

In addition to the solder alloy and the flux, the solder paste contains additives that adjust its rheological properties. These include thixotropic agents, which prevent the solder particles from settling, and solvents to adjust the viscosity. A suitable viscosity is essential for use in stencil printing and subsequent wetting during the reflow process.

The process of ageing results in the separation of the solder metal powder and the flux, which also gives rise to a change in the rheological properties. Consequently, solder pastes have a restricted shelf life. The average shelf life of solder pastes is approximately six months when stored in a cool environment between 5 °C and 15 °C. For utilization, the solder paste must be heated to room temperature and subsequently consumed or discarded, as prolonged storage is no longer feasible. The presence of residual quantities, particularly those in a desiccated state, or adhesions within the container, necessitates an increasing degree of separation between the solder paste components. Consequently, solder paste is sold in smaller containers or packaging units, such as cups, cartridges or syringes, with a typical filling quantity of approximately 100 g to 500 g.

2.3. *Recycling of solder paste*

In the process of recycling solder pastes, the preservation of the properties of the alloy is of paramount importance. This is achieved by ensuring that the powder is not significantly altered, thereby preserving its ideal spherical form. Only by adhering to these principles, the recycled material can be reused in the production of new solder paste. In an ideal scenario, the other components - namely, flux, additives and container material - would also be subject to recycling and reintroduction into the manufacturing process.

In the past, various concepts and methods for reducing pollutants, reusing and recovering solder paste waste have been developed, focussing on environmental and health aspects and the legal framework. The legal framework conditions include, for example, compliance with environmental standards and directives such as the RoHS directive (Das europäische Parlament und der Rat der europäischen Union, 2024).

In addition to the fundamental strategies for recycling electronic waste, a number of approaches have been identified for recycling solder pastes (Prasad et al., 2021). These include mechanical, chemical and thermal processes for separating solder paste from other materials (Hwang, 1992). Initial analyses comparing the soldering quality of recycled and conventional solder paste have also been published (Tanaka et al., 2012). Furthermore, studies have been conducted on the reduction of pollutants and the minimization of the release of lead and flux residues (Chang et al., 2022).

The study of lead-free solder pastes represents a significant area of research (Lau and Lee, 2020; Lee et al., 2015; Bath, 2007; Evans and Engelmaier, 2007). Yoo et al. (2012) describe the development of a hydrometallurgical process for the recycling of lead-free waste solder based on nitric acid leaching and the subsequent separation of silver and copper by a precipitation reaction of silver and chloride ions or cementation. A recycling process was developed for the recovery of tin, bismuth, copper and resin from lead-free solder paste. This process includes swelling as well as ammonia and hydrochloric acid leaching (Jeon et al., 2017).

The REACT-EU research project involved an investigation into the physical separation processes required to isolate solder powder (Stannol GmbH & Co. KG, 2024). The investigations conducted at the University of Rostock revealed that the quality of the secondary tin was comparable to that of the primary tin. To achieve this, a combination of light and scanning electron microscopic investigations, along with thermal analyses, was employed. Additionally, a prototype recycling concept for tin waste and a system for the automated processing of solder pastes were developed. The research project REACT-EU, was carried out from March 2022 to February 2023 by Stannol, MTM Ruhrzinn, Fraunhofer FIT, Fraunhofer UMSICHT and bpc specialties. The findings of this project serve as the foundation for the research proposal and the realization of the ZWP research project.

Furthermore, various manufacturers of solder pastes offer collection points for the delivery of solder pastes for internal recycling (for example: Rotec BV, 2024; Tim-Nordic OY, 2024; Indium Corporation, 2024). Seika Machinery Inc. also sells a system that enables 90% of solder paste to be recovered as solder bars, whereby flux and solder are also separated (Seika Machinery Inc, 2024).

The conclusion is that there are various concepts and methods for reducing pollutants, reusing and recovering solder paste waste, but a circular economy for solder paste does not currently exist.

3. Zero Waste Paste research project

The objective of the ZWP research project is to develop a circular economy with 'zero waste', whereby solder paste waste can be recycled, the raw materials it contains recovered and fed into the manufacturing process for new solder paste. In the recovery of raw materials, the solder metal, flux and container material are all considered. In order to successfully realize the research project, the following sub-goals are being pursued:

(1) The development of a logistics system
(2) The development of a process and a system prototype
(3) The development of a circular economy

The development of a logistics system that incorporates standardized waste labelling represents a fundamental step towards the efficient and unmixed recovery of raw materials and comprises two aspects: the recycling cycle for solder powder and potential sorting options for solder paste

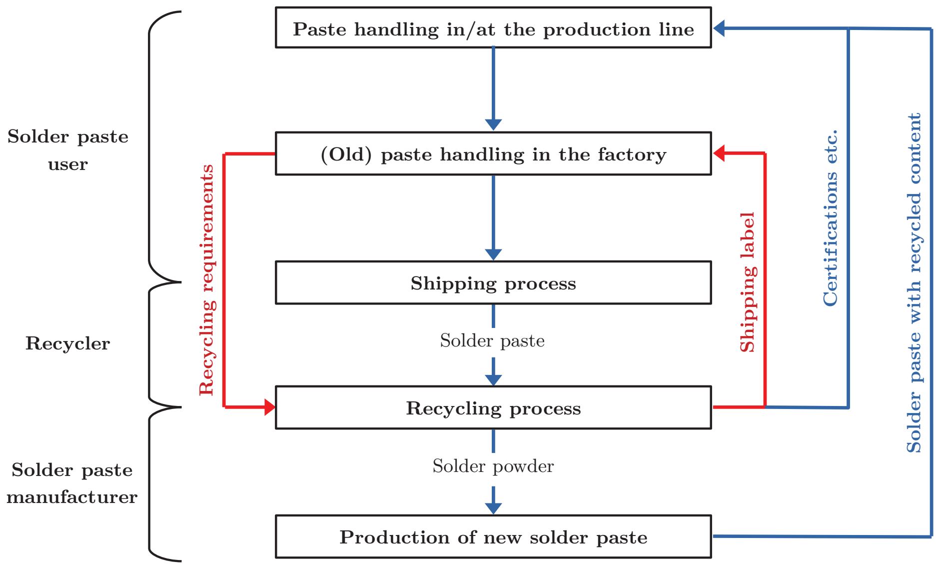

Fig. 2. A potential zero waste paste cycle or circular economy concept

waste to facilitate the ZWP cycle (Figure 2). Furthermore, the implementation of such a system facilitates the tracing of waste and pre-sorting, which in turn optimizes transport routes, conserves resources and reduces the environmental impact.

A system prototype is currently being developed and will soon be put into operation. This will enable the efficient and gentle recovery of all three solder paste components (solder metal / powder, flux and container material) in an automated process. The system prototype will be validated with different solder paste compositions and alloys in order to test its general applicability.

The objective of raw material recovery and recycling is to return the raw materials to the manufacturer of solder paste, thereby establishing a raw material cycle that does not currently exist in this form. Alternative utilization options are also being examined with a view to using not only the solder metal but also the flux and the container material for the production of new solder paste, for example.

4. Development of the washing process

The design of the washing process constitutes the elementary initial step in the development of a process for the automated, efficient and gentle recovery of raw materials from solder paste components (solder metal, flux and container material). A range of cleaning and separation tests were carried out in order to test suitable processes, solvents etc. The following objectives are pursued:

(1) Removing the solder paste residue from the container
(2) Cleaning the container of any remaining solder paste residue
(3) Separating the solder metal from the other components (flux, additives etc.)
(4) Cleaning the solder metal

An alternative approach involves the utilization of liquid nitrogen to facilitate the dissolution of substantial quantities of solder paste residue from the container in the initial step. This method is particularly advantageous in instances where containers of solder paste that are (still) almost full still require recycling.

4.1. *Liquid nitrogen*

Tests were conducted using liquid nitrogen to remove the majority of solder paste from the container. The objective of this process is to freeze the solder paste in such a manner that it is completely

Fig. 3. Separation of solder paste from the solder paste container with liquid nitrogen: Frozen solder paste separated from the solder paste container by mechanical treatment

separated from the paste container. This approach is intended to facilitate the complete removal of the solder paste from the container without leaving any residue. This objective was accomplished by subjecting the solder paste container to a nitrogen bath for approximately five minutes. As demonstrated in Figure 3, the experimental findings indicate that the solder paste could be almost completely removed through mechanical action.

The solder paste components experienced partial separation due to the freezing process, resulting in the separation of components such as flux from the solder paste during subsequent thawing. At this stage, the extent to which liquid nitrogen affects the structure of solder paste remains to be elucidated. This issue will be examined in greater detail as the project progresses. The solder paste container sustained damage due to the mechanical impact, a consequence of the material's strong brittle behavior during the freezing stage. However, a negligible quantity of solder paste remains in the container. These components must be removed from the solder paste container during subsequent cleaning steps so that it can be recycled.

4.2. *Solvents*

A series of cleaning tests were conducted in an ultrasonic bath utilizing a range of solvents to facilitate the separation of solder metal and flux. The selection of solvents used for this purpose included both low-boiling and highly flammable substances and initially did not exclude any solvents in order to extend the state of research:

- Aceton
- Ethylacetat
- 2-Propanol
- Isopropanol
- Solvents based on glycol ethers
- Solvents based on sulfoxide
- Essential oils
- ...

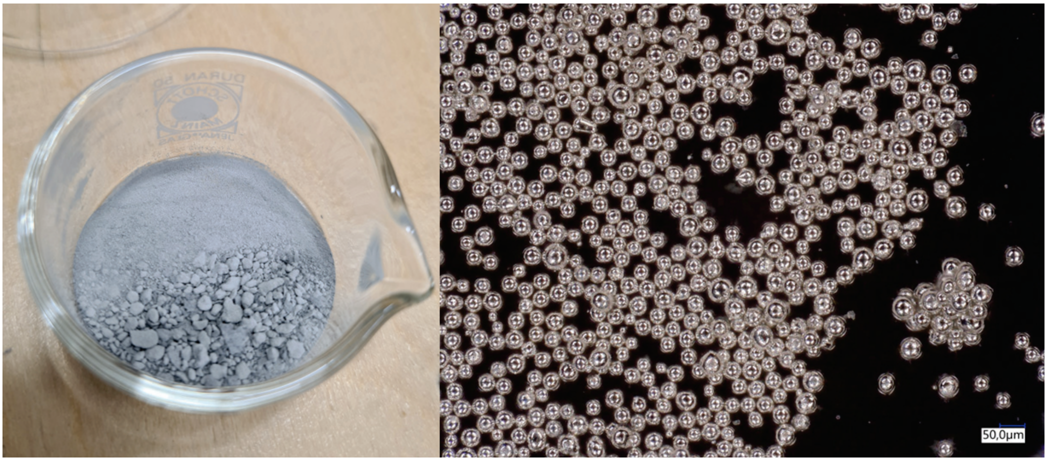

Fig. 4. Left: Solder powder release using isopropanol and ultrasound; Right: Phenom X REM image of the solder powder

Each experiment was conducted in an ultrasonic bath for a duration of approximately 15 minutes. The quantity of solvent utilized ranged from 10 ml to 15 ml. Subsequent to this, filtration and drying processes are employed. The collected solder powder, which was subjected to a cleaning process using isopropanol, exhibited minimal clumping (Figure 4). This phenomenon must be addressed through additional cleaning steps. However, it was observed that the organic components could be effectively removed.

5. Summary and outlook

Solder paste is an indispensable component in the manufacture of electronic components and the assembly of printed circuit boards. However, its shelf life is limited, and it is currently usually disposed of as hazardous waste. This means that the solder paste components (solder metal, flux, additives, solder paste containers etc.) are not recycled. The Zero Waste Paste research project aims to develop a circular economy in which solder paste residues are returned to the manufacturing process, thereby ensuring that as many components as possible can be reused for the production of new solder paste. In addition to the establishment of a logistics system, a cleaning process and a fully automated cleaning prototype are being developed for this purpose. In order to harmonize the cleaning process, various procedures and cleaning agents were tested in the first step to remove the solder paste from the container and to separate the solder paste components solder metal, flux and additives from each other. A significant quantity of solder paste residue was removed from the container using liquid nitrogen, leaving only a minimal residue behind. Various solvents were also tested for their efficacy in removing solder paste residues from the container, with initial usable results being achieved with isopropanol. However, further chemical analyses are required to determine the suitability of the recycled solder powder, based on its purity, flowability and solderability. Subsequent tests are planned for substances including paraffin, dichloroethane, organic carbonates and chlorophorm.

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