

Impact of Solder Powder Size on Cleaning Efficiency in Chip Resistor Assemblies for Future Advanced Packaging

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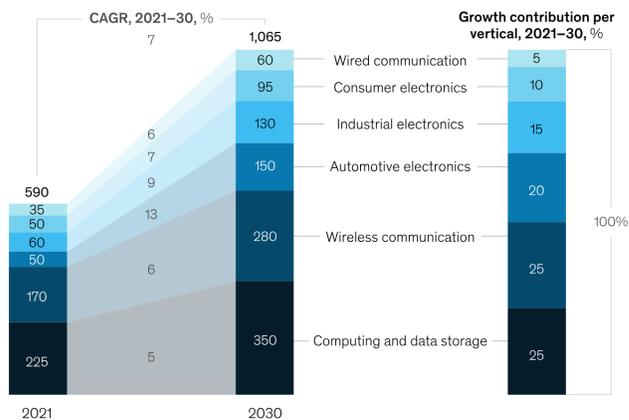
ABSTRACT

This study evaluates the efficiency of various cleaning chemistries under controlled process conditions, including conveyor belt speed and concentration, for the removal of water-soluble flux residues using a test vehicle incorporating different chip resistors, MLF and BGA components. The influence of solder powder size on flux composition was examined, with smaller powder sizes exhibiting increased flux activator content, leading to higher residue accumulation and greater cleaning complexity. By systematically testing different solder powder sizes T5 (25-15 μm), T6 (15-5 μm), and T7 (11-2 μm) this research aims to elucidate their effects on defluxing efficiency and residue removal. Experimental procedures involved assembling test vehicles having MLF-68, BGA-208 and resistors of varying sizes, followed by controlled reflow and standardized defluxing using aqueous-based defluxing systems. Post-defluxing, analysis was conducted using visual inspection to quantify and characterize flux residues. The study specifically addresses the challenges of flux removal under low-standoff components, where restricted access exacerbates residue entrapment. Results indicate that different solder powder sizes require selection of defluxing chemistry and process parameters. Further studies will aim to refine cleaning methodologies and investigate interactions between solder powder size, flux chemistry, and process conditions to enhance cleanliness and reliability in advanced semiconductor packaging.

Keywords: Advanced Packaging, Solder Powder Size (T5-T7), Miniaturization, Low-standoff, Electrical Leakage, Reliability, Solder Interconnects

INTRODUCTION

The accelerated growth of Advanced Packaging (AP) technologies has significantly reshaped the semiconductor landscape, enabling high-density integration, functional enhancement, and form factor reduction to meet the demands of emerging technologies such as 5G, IoT, ADAS, EVs, medical electronics, and aerospace systems [1].



Note: Figures are approximate.
Figure 1. Global semiconductor market value by vertical, indicative, \$ billion

Among the AP platforms, System-in-Package (SiP) plays a pivotal role by incorporating multiple semiconductor dies, passive components, and interconnects within a compact module. This architectural flexibility facilitates performance gains, power efficiency, and miniaturization required by high-performance electronics [2].

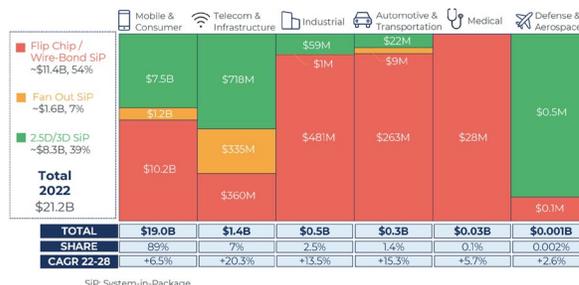


Figure 2. System-in-Package 2023 report, Yole Intelligence, 2023.

In devices such as smartphones, wearables, and mmWave communication modules, there is increasing adoption of ultra-miniature passive components notably 01005 and 008004 chip resistors to enable dense circuit designs without increasing package size. These design trends support higher functional integration but introduce substantial challenges in manufacturing, particularly in downstream cleaning processes.

1.0 CLEANING CHALLENGES IN SiP

One of the most pressing reliability concerns in SiP manufacturing is flux residue removal, especially when using water-soluble solder pastes. The dense component layout reduced standoff heights ($<50\mu\text{m}$), and intricate interconnect geometries create restricted cleaning zones, where flux residues may be physically shielded from the cleaning agent. If not completely removed, residues can lead to electrochemical migration, dendritic growth, corrosion, and electrical leakage, all of which can severely compromise long-term electrical reliability [3].

The situation is further complicated by advancements in solder paste formulation. As solder powder sizes decrease (e.g., T5, T6, T7), their increasing surface area requires greater flux activator content, which consequently results in higher residue volumes and altered chemical behavior. These residues tend to be more reactive, hydrophilic, and sticky in nature making them harder to remove under traditional cleaning setup.

DI-water-only cleaning is often insufficient for modern SiP assemblies. Limited penetration, lack of surfactant-driven wetting, and insufficient chemical reactivity prevent DI water from adequately cleaning under low-profile components [4][5][6]. As a result, engineered aqueous-based cleaning chemistries have been developed to provide better penetration, improved solubilization of residues, and compatibility with sensitive materials commonly used in SiP technology.

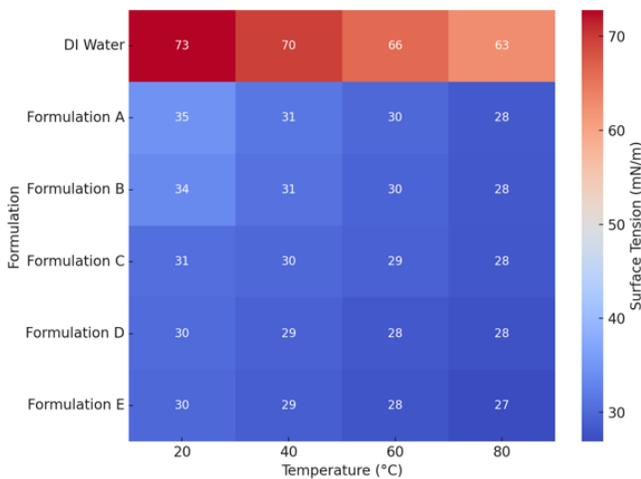


Figure 3. Heatmap of surface tension across formulations and temperatures.

The heat map illustrates the surface tension behavior of various cleaning agents and DI-water across temperatures ranging from 20°C to 80°C . As shown, all cleaning formulations maintain significantly lower surface tension values compared to DI-water, with minimal variation across the temperature range. This consistent low surface tension is critical in ensuring effective cleaning in advanced packaging applications, as it enhances wetting and penetration under

low standoff components. The data demonstrates the superior wetting performance of formulated chemistries, especially at elevated temperatures where DI-water surface tension remains substantially higher.

To achieve effective cleaning, optimization of process variables based on the T.A.C.T. framework Time, Action (mechanical force), Chemical energy, and Temperature is essential. These parameters must be tailored for the specific flux chemistry and residue profile associated with each solder powder size [7].

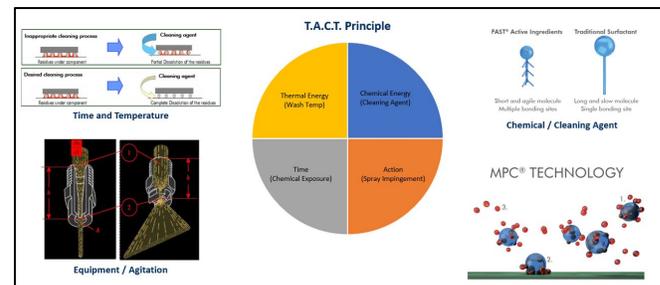


Figure 4. T.A.C.T Principle

2.0 MAIN STUDY FOCUS

This study investigates the influence of solder powder size and process speed on the cleaning efficiency of water-soluble flux residues in chip resistor assemblies representative of advanced SiP packaging. Test vehicles incorporating various chip resistor sizes were assembled using solder pastes with controlled powder distributions: T5 ($25\text{--}15\mu\text{m}$), T6 ($15\text{--}5\mu\text{m}$), and T7 ($11\text{--}2\mu\text{m}$).

The research focuses on evaluating:

- How decreasing solder powder size alters flux composition & residue behavior,
- The effectiveness of aqueous-based cleaning chemistries under controlled T.A.C.T. conditions,
- The challenges of cleaning under low-standoff and high-density SiP components, and
- Recommendations for optimized cleaning strategies to ensure long-term electrical reliability in advanced packaging applications.

By demonstrating the relationship between powder size, flux formulation, and defluxing performance, this work provides critical insights into cleaning process design for next-generation miniaturized assemblies.

3.0 SOLDER PASTE FORMULATION

Solder powder is classified by type according to IPC J-STD-005A. For SMT applications, Types 3-5 are commonly used, while SiP applications typically require Types 6 and 7, with future applications expected to use Type 8 & 9. Relevant powder types for SiP are shown in Table 1.

Table 1. Solder powder (SAC305) types with powder size range and applications

Powder Type	Powder Size Range (um)	Approximate Surface Area Ratio	Application
5	25-15	1.9	Up to 01005 & Flip Chips with pitch 200µm
6	15-5	3.7	Up to 008004 & Flip Chips with pitch 150µm
7	11-2	5.6	Up to 008004 & Flip Chips with pitch 100µm

The development of ultra-fine Type 5,6 and 7 powders, with high sphericity, processed using Heraeus’s proprietary Welco™ technology as shown in Fig.5, has led to the creation of water-soluble solder pastes that ensure consistent print volumes and adherence to the stringent requirements of stencil openings and pitches. The three solder pastes selected for this study are commonly used in fine-feature advanced packaging applications. Heraeus Materials pastes A, B & C which are water-soluble pastes, chosen for its widespread use in high-volume manufacturing.

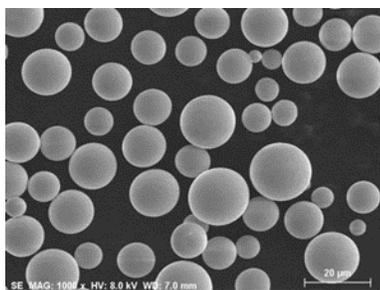


Figure 5. Welco™ Solder powder Type 7 (SAC305 alloy), Powder size distribution (PSD) >90% and powder size 2-11µm

The test vehicle featured ENIG surface finish. The reflow profile is shown below and all the solder pastes were soldered using lead-free profile under air-atmospheric condition with peak temperature set around 240°C.

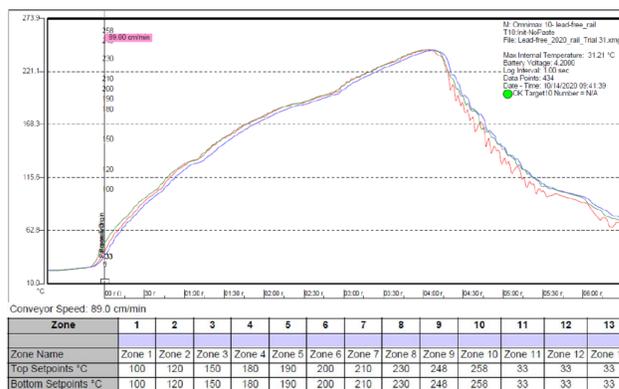


Figure 6. Soldering profile used in this study

CLEANING AGENT USED

Seven (7) different kinds of aqueous-based cleaning agents were evaluated during this study. They are identified as shown below:

- Formulation ‘A’ – MPC® Technology-based next-gen pH-neutral with corrosion inhibition package.
- Formulation ‘B’ – MPC® Technology-based pH-neutral with corrosion inhibition package.
- Formulation ‘C’ – FAST® - based pH-alkaline with corrosion inhibition package for water-soluble fluxes.
- Formulation ‘D’ – MPC® Technology-based pH-alkaline with minimal corrosion inhibition package.
- Formulation ‘E’ – FAST® - based pH-alkaline with minimal corrosion inhibition package.
- Formulation ‘F’ – FAST® - based pH-alkaline with corrosion inhibition package.
- Formulation ‘G’ – MPC® technology-based pH-neutral with minimal corrosion inhibition package.

These cleaning agents are formulated specifically targeting semiconductor segment in the field of advanced substrates including 2.xD/3D, BGAs and SiPs. They offer optimal surface conditions for subsequent processes such as underfill, wire bonding, and molding. The formulations with corrosion inhibition package offer a high level of material compatibility with sensitive metals and is recommended for use in spray-in-air system processes.

TEST VEHICLE USED

The test vehicle used in this study is shown below. In this study, 0402, 0603, 0804, SOT-23, 1206 and 1210 components were selected for the cleaning evaluation to provide a practical yet representative benchmark of cleaning performance. While smaller components such as 0201, 01005 and 008004 are increasingly used in advanced packaging especially in complex front-end modules (FEMs), the selected sizes offer meaningful insight into flux residue entrapment and cleaning agent accessibility under common standoff and pitch constraints.

This selection enables a controlled comparison of how solder powder size and flux formulation affect the residue removal. The results provide a reliable basis for optimizing cleaning chemistry and process settings before extending them to high-density SiP assemblies with finer component geometries.

The area highlighted in red indicates the components that were populated for this study.

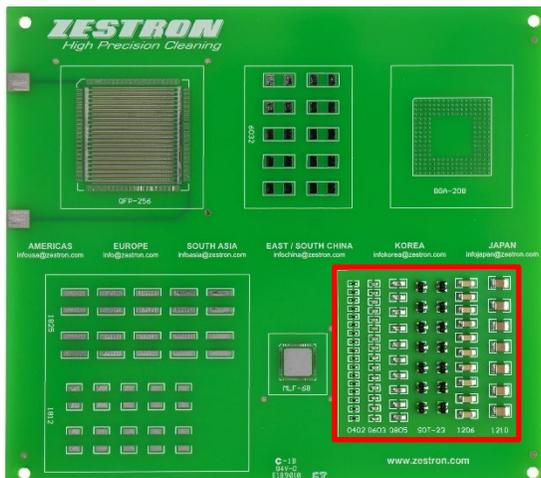


Figure 7. Representative picture of test vehicle populated with components for this study

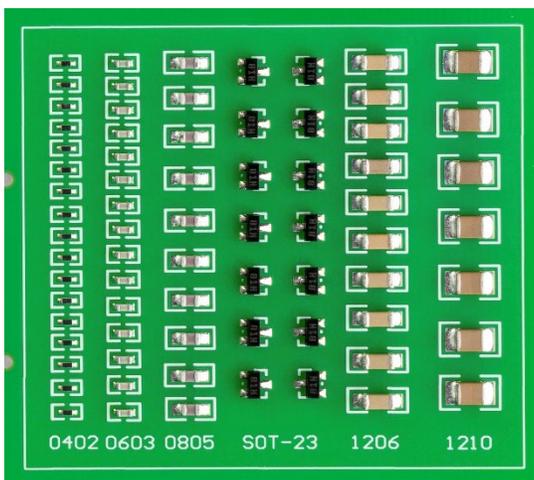


Figure 8. Close-up photograph of chip array area

EXPERIMENT PERFORMED

A conveyORIZED spray-in-air inline cleaner was employed in this study. This study maintained uniformity in temperature and pressure settings in all the sections of the inline cleaner, as process optimization was not the objective. However, two different concentrations and varying belt speeds were used.

For all the cleaning formulations, the test plan was executed utilizing the parameters as detailed in Table 2.

Table 2. Test plan for the study

Solder Paste	Concentration (%)	Belt Speed (fpm)
Heraeus Water-soluble pastes (Type 5, 6 & 7)	5.0%	1.0 fpm
		2.0 fpm
		3.0 fpm
	7.5%	1.0 fpm
		2.0 fpm
		3.0 fpm

The process settings used in the spray-in-air inline cleaner are detailed in Table 3.

Table 3. Inline cleaner process parameters

Wash Stage	
Equipment	ITW AS200C Inline Cleaner
Cleaning Agents	Formulations ‘A’, ‘B’, ‘C’, ‘D’, ‘E’, ‘F’ & ‘G’
Chemical Concentration	Refer to earlier table
Conveyor Belt Speed	
Wash Spray Configuration	Top: 8-spray intermix manifold Bottom: 8-spray manifold
Pre-Wash Pressure (Top/Bottom)	50 PSI / 30 PSI
Wash Pressure (Top/Bottom)	70 PSI / 20 PSI
Wash Hurricane Pressure (Top/Bottom)	40 PSI / 40 PSI
Wash Temperature	150°F
Chemical Isolation Pressure (Top/Bottom)	25 PSI / 25 PSI
Rinsing Stage	
Rinsing Agent	DI water
Wash Spray Configuration	Top: 8-spray intermix manifold Bottom: 4-spray manifold
Rinse Pressure (Top/Bottom)	70 PSI / 20 PSI
Rinse Hurricane Pressure (Top/Bottom)	40 PSI / 20 PSI
Rinse Temperature	150°F
Final Rinse Pressure (Top/Bottom)	25 PSI / 25 PSI
Final Rinse Temperature	Room Temperature
Drying Stage	
Drying Method	Hot Circulated Air
Drying Temperature (D1)	180°F
Drying Temperature (D2)	210°F
Drying Temperature (D3)	210°F

Cleanliness assessment was conducted per IPC-A-610 Rev H standards, focusing on both test vehicle surface and under-component cleanliness. Visual inspections were conducted utilizing a 40X microscope magnification supported by a polarized filter to enhance contrast.

Under-component cleanliness evaluation involved mechanically shearing all components from the test vehicles and categorizing visual inspection ratings into “fully cleaned” or “not cleaned” [8].

For each component type, the cleanliness assessment was independently carried out by multiple Application Engineers and the results aggregated, averaged, and expressed as a percentage of under-component cleanliness using the formula:

$$\text{Average Cleanliness Level} = \frac{\text{Number of fully cleaned components}}{\text{Total number of components on test vehicle}}$$

Representative pictures of under-component cleanliness (before cleaning, partially cleaned and fully cleaned) is shown below in figures 9-26.

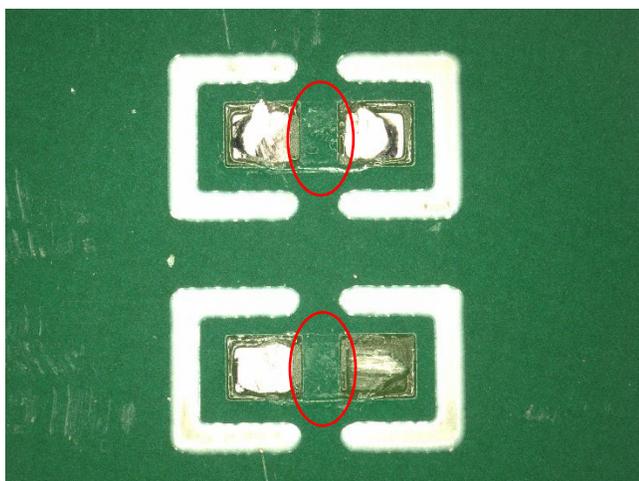


Figure 9. 0402 Component Before Cleaning

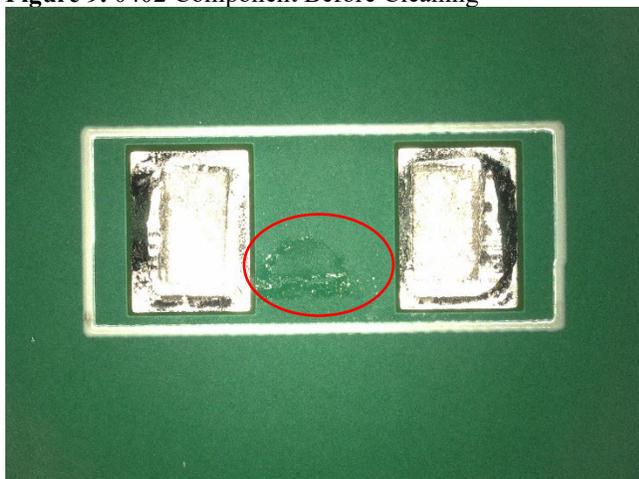


Figure 10. 0402 Component (partially cleaned – showing residues)

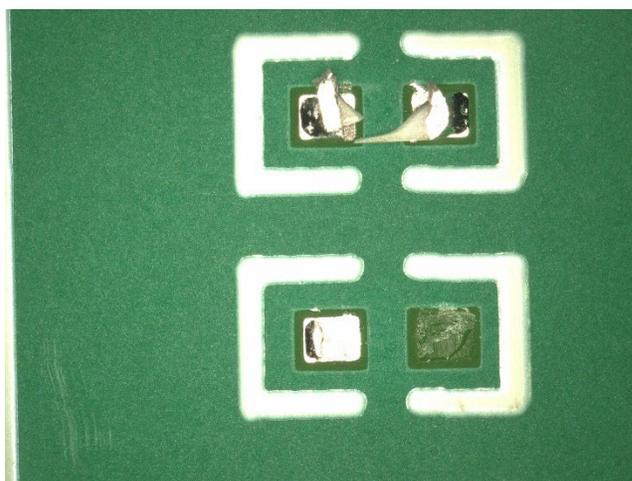


Figure 11. 0402 Component Fully Clean

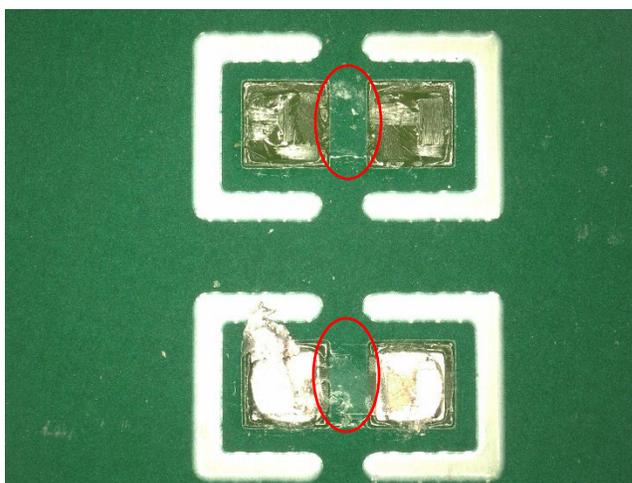


Figure 12. 0603 Component Before Cleaning

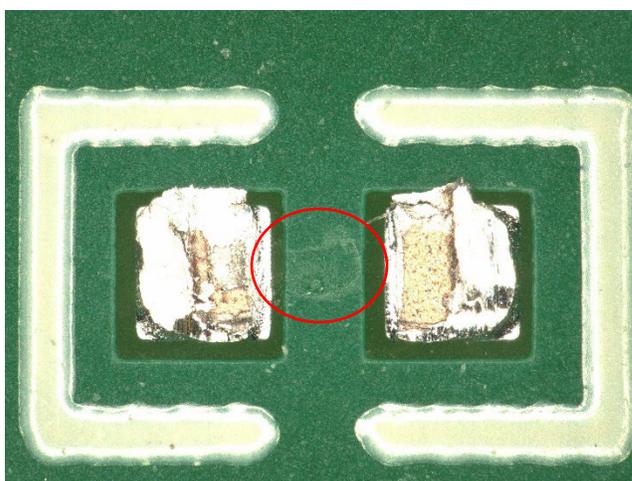


Figure 13. 0603 Component (partially clean – showing residues)

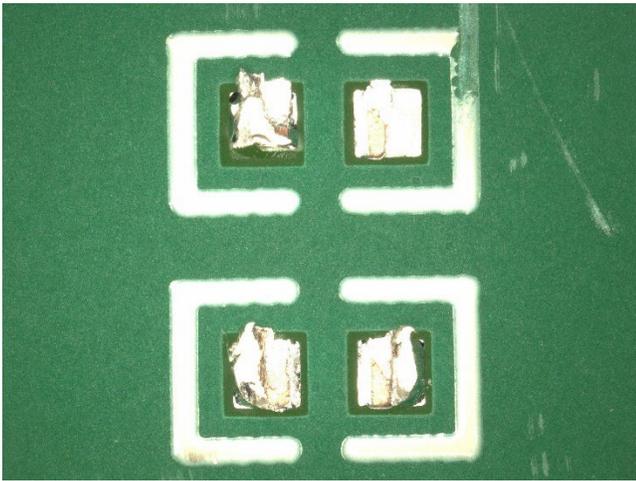


Figure 14. 0603 Component Fully Clean

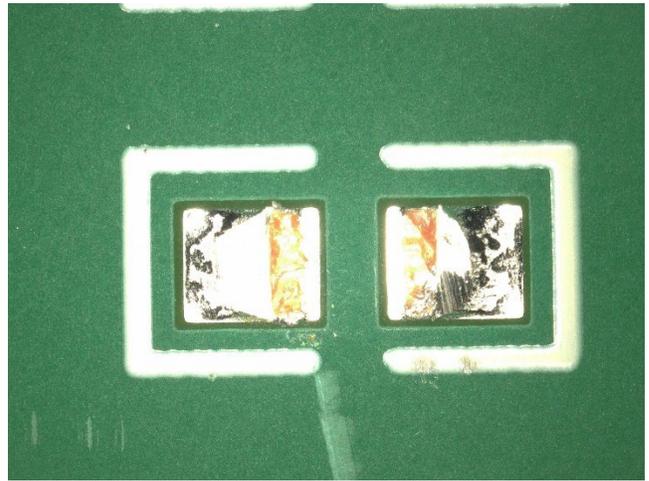


Figure 17. 0805 Component Fully Clean

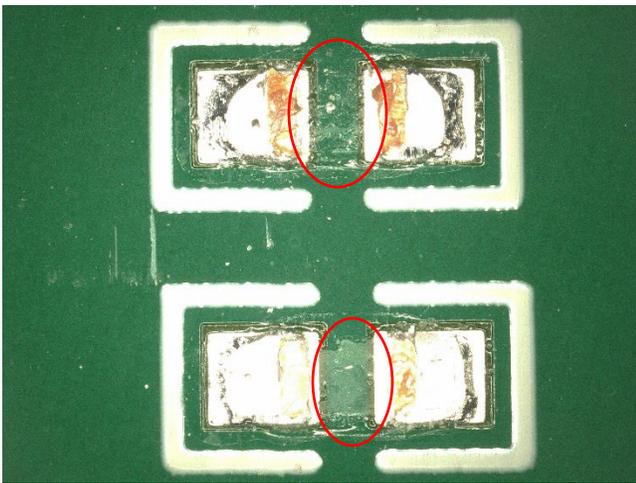


Figure 15. 0805 Component Before Cleaning

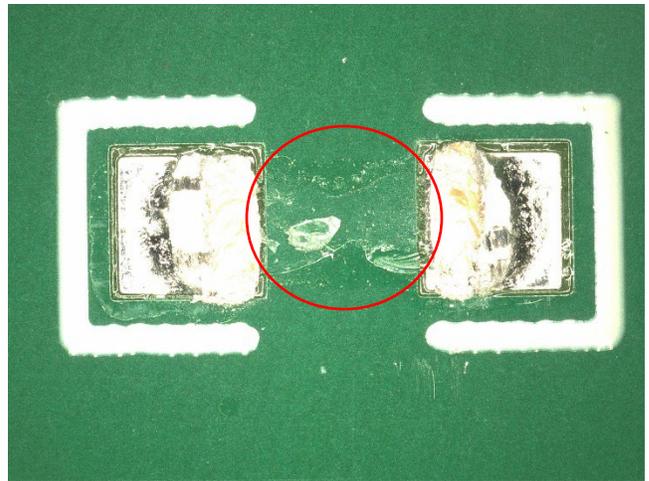


Figure 18. 1206 Component Before Cleaning

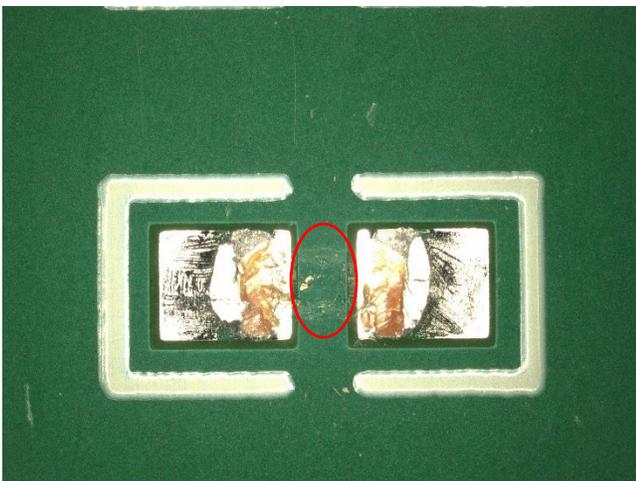


Figure 16. 0805 Component (partially clean – showing residues)

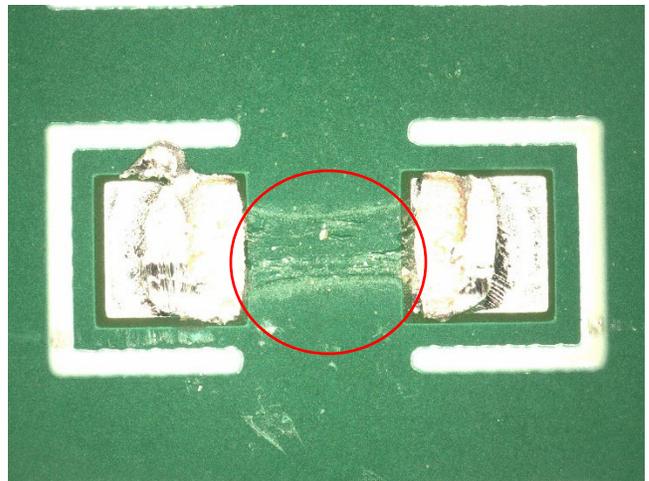


Figure 19. 1206 Component (partially clean – showing residues)

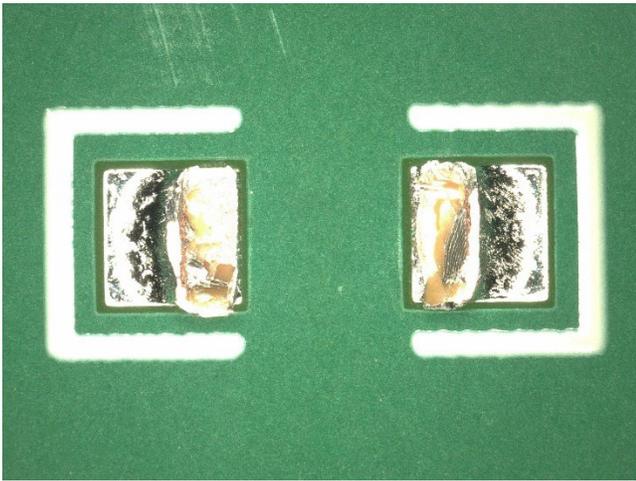


Figure 20. 1206 Component Fully Clean

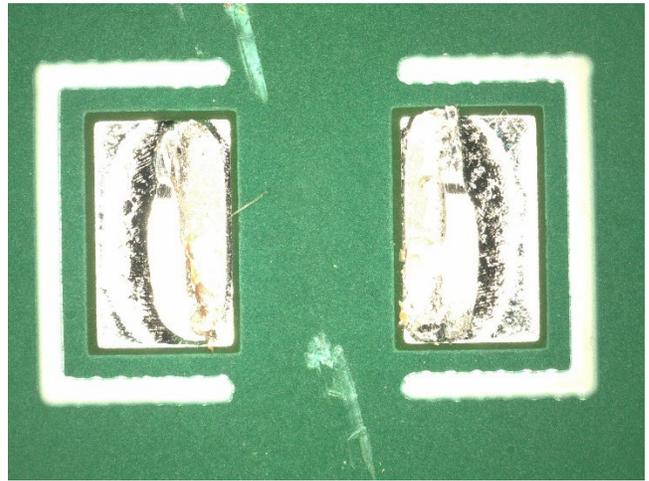


Figure 23. 1210 Component Fully Clean

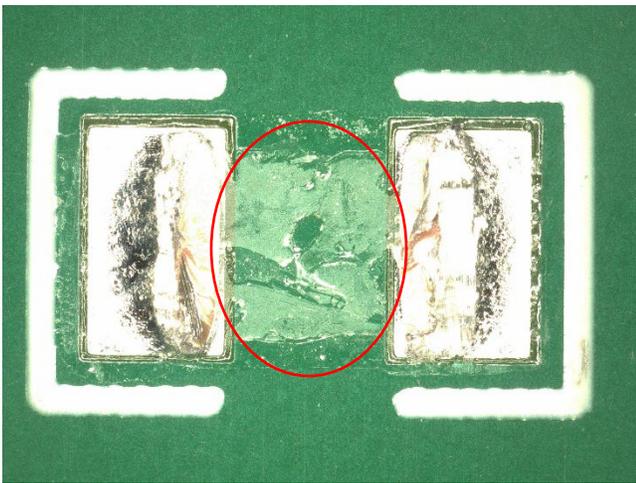


Figure 21. 1210 Component Before Cleaning

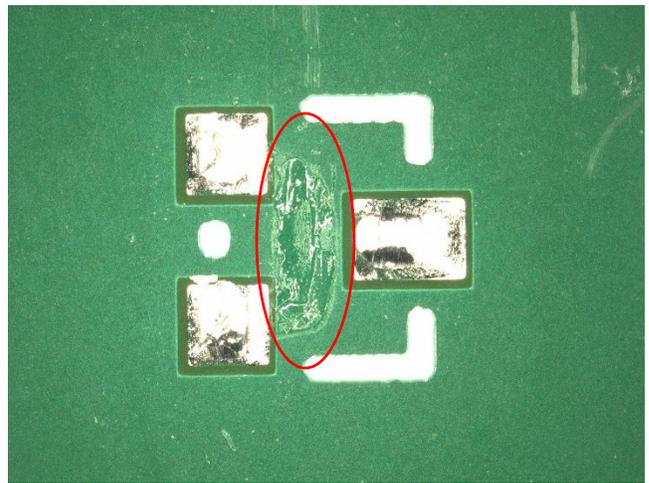


Figure 24. SOT-23 Component Before Cleaning

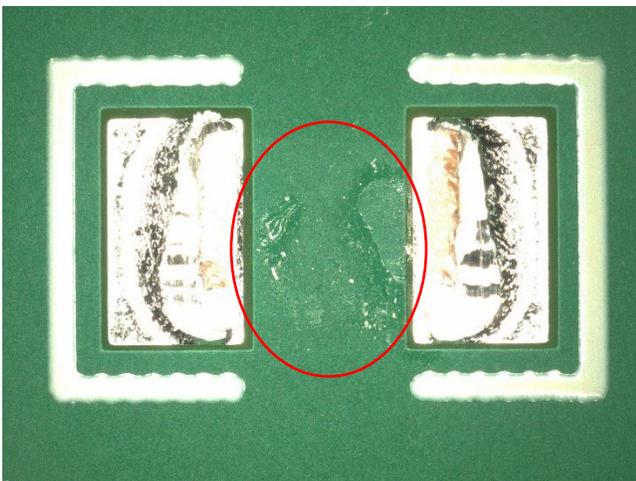


Figure 22. 1210 Component (partially clean – showing residues)

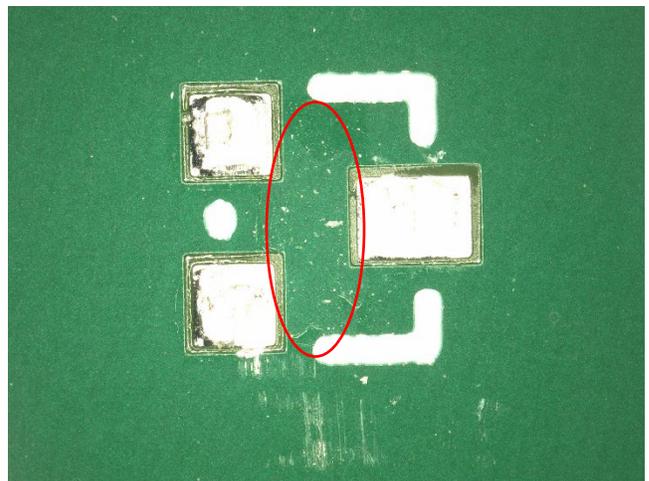


Figure 25. SOT-23 Component (partially clean – showing residues)

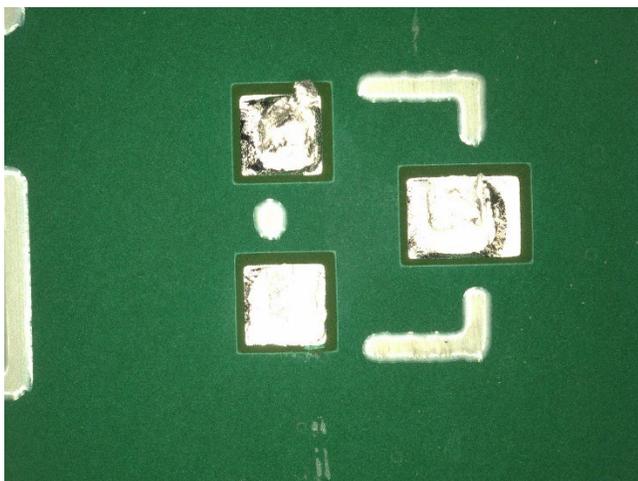


Figure 26. SOT-23 Component Fully Clean

RESULTS:

The comprehensive cleanliness assessments are detailed in figures 27-32.

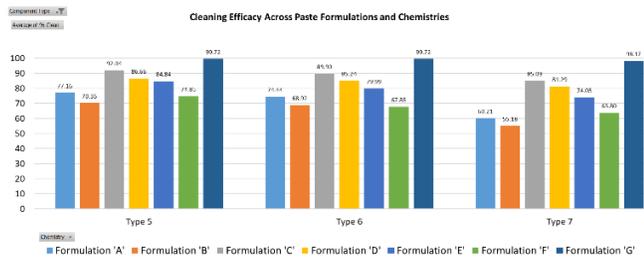


Figure 27. Cleaning Efficacy Across Pastes Formulations And Chemistries

As observed in Fig. 27., Formulation ‘G’ consistently delivers the highest cleaning efficacy across all solder paste types (T5, T6 & T7) achieving ~99.7% and ~98.2% cleanliness, indicating superior performance regardless of flux load or particle size. Cleaning performance remains largely consistent across T5 to T7 powder sizes, with only marginal differences observed. This suggests the formulation effectively manages residue removal despite the increased flux volume and together capillary spaces associated with finder powders.

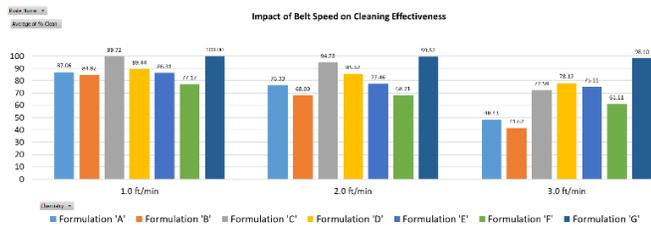


Figure 28. Influence Of Belt Speed On Flux Residue Removal

Fig. 28 indicates that cleaning effectiveness decreases with increasing belt speed across all formulations, indicating that

higher conveyor speeds reduce chemical exposure time leading to less residue removal. Formulation ‘G’ maintains the highest cleaning performance at all belt speeds.

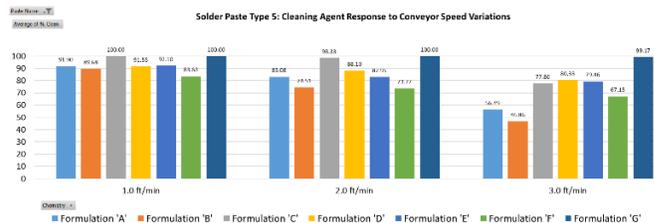


Figure 29. Solder Paste Type 5: Cleaning Agent Response To Conveyor Speed Variations

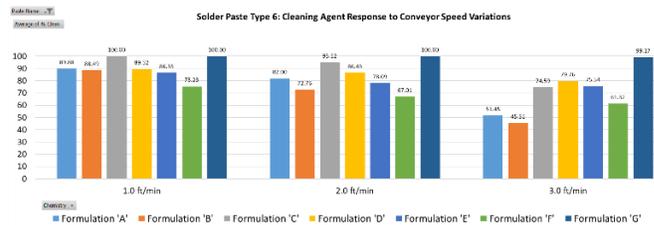


Figure 30. Solder Paste Type 6: Cleaning Agent Response To Conveyor Speed Variations

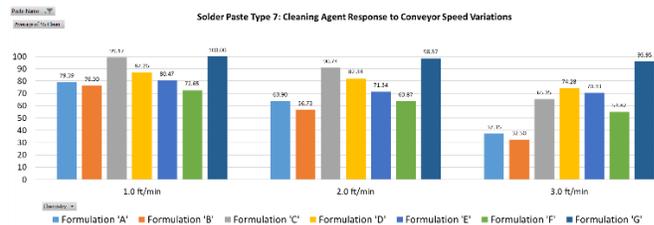


Figure 31. Solder Paste Type 7: Cleaning Agent Response To Conveyor Speed Variations

Figures 29-31 indicate across all solder paste types (T5-T7), cleaning efficiency consistently declines with increased conveyor speed for most formulations with Formulation ‘G’ maintaining >95% performance indicating robust process regardless of flux volume or process constraints.

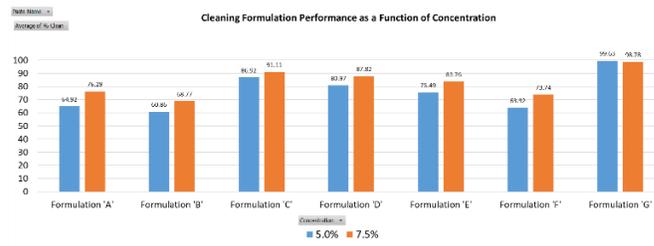


Figure 32. Cleaning Formulation Performance as a Function of Concentration

In case of Fig. 32, all formulations show improved cleaning efficiency with increased concentrations from 5.0% to 7.5% confirming that cleaning strength directly influences flux residue removal performance.

Table 4. Summary of Cleaning Performance by Formulation and Concentration

Formulation	5.0% Conc. (% Clean)	7.5% Conc. (% Clean)	Performance Trend
A	64.92	76.29	Strong improvement with concentration
B	60.86	68.77	Lowest performance, limited improvement
C	86.92	91.11	High performance with slight gain
D	80.97	87.82	Good performance with moderate gain
E	75.49	83.76	Moderate performance but improved with concentration
F	63.92	73.74	Scalable with moderate performance gain
G	99.63	98.78	Excellent performance at all concentration levels

From the above table, it was identified that Formulation ‘G’ demonstrates exceptional cleaning performance at both 5.0% and 7.5% concentrations while Formulations ‘C’ and ‘D’ also exhibit strong results with less variation from concentration standpoint. Formulations ‘A’, ‘B’ and ‘F’ show greater dependency on higher concentration to improve cleaning effectiveness with Formulation ‘B’ being the least effective overall. Formulation ‘E’ shows moderate performance at 5.0% but improves significantly at 7.5% indicating it benefits from higher concentration.

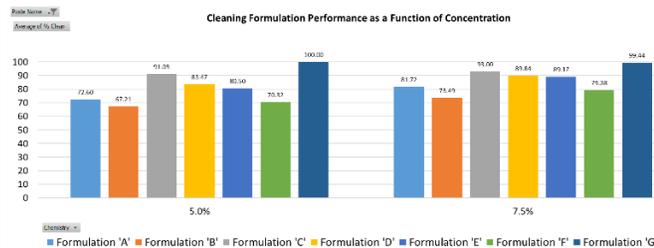


Figure 33. Solder Paste Type 5: Cleaning Efficiency vs Formulation Concentration

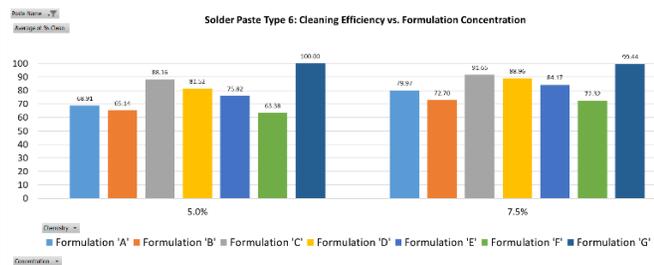


Figure 34. Solder Paste Type 6: Cleaning Efficiency vs Formulation Concentration

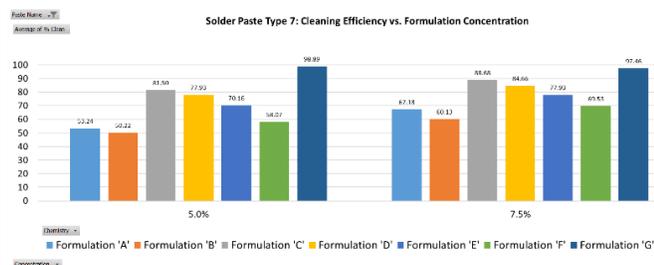


Figure 35. Solder Paste Type 7: Cleaning Efficiency vs Formulation Concentration

Figures 33-35 indicates that Formulation ‘G’ consistently provides highest cleaning performance across all solder paste

types and concentrations, maintaining >97% even for the most challenging Type 7 paste, demonstrating superior chemical robustness. Formulations ‘C’, ‘D’ and ‘E’ show good scalability with concentration with performance improving across all paste types. However, the cleaning effectiveness declines significantly for lower-performing formulations ‘A’, ‘B’ and ‘F’ especially on Type 7, indicating the need for optimized chemistry when dealing with ultra-fine powder sizes.

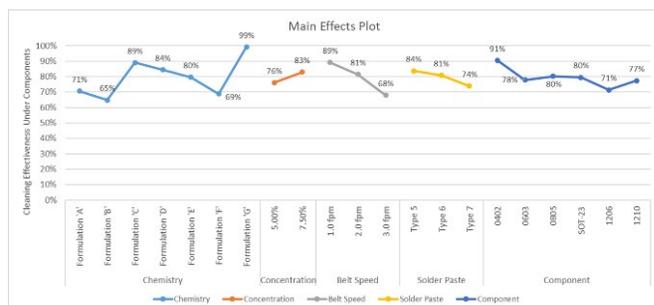


Figure 36. Main Effects Plot

The main effects plot in Fig. 36 indicates the influence of key process parameters on cleaning effectiveness under components. Amongst all factors, chemistry selection has the most profound effect with Formulation ‘G’ achieving the highest cleaning effectiveness (99%) and Formulation ‘B’ providing the lowest (65%). Increasing concentration from 5.0% to 7.5% boosts cleaning performance by ~7% while reducing the belt speed from 3.0 fpm to 1.0 fpm yields a significant gain (~21%) implying that chemical exposure time is of utmost importance.

Additionally, solder paste type 5 achieved a cleanability of 84% compared to 74% for Type 7, indicating only a marginal difference in cleaning performance. This suggest that the formulation remains largely effective across finer powder sizes, despite the increased cleaning challenges associated with reduced standoff and tighter capillary structures.

CONCLUSION:

- This study confirmed that cleaning chemistry selection is the most dominant factor affecting flux residue removal in advanced packaging. Among the tested chemistries, Formulation ‘G’ consistently delivered >97% cleaning effectiveness across all solder paste types, belt speeds and concentrations.
- Minor differences in solder paste type and powder size can affect residue behavior. While the cleanability between Type 5 and Type 7 is marginal, these subtle variations are increasingly critical as package miniaturization advances.
- Belt speed directly impacted the cleaning efficiency. Higher conveyor speeds reduced the contact time and limited chemical interaction especially under low standoff components, which reinforces the importance of chemical exposure time for complex SiP assemblies
- The results also showed that component geometry particularly large body size and lower standoff height

led to greater cleaning difficulty due to shadowing and capillary entrapment. This directly correlates with SiP architectures where tightly spaced 0201, 01005 and 008004 components are more common and will create highly inaccessible/challenging regions.

- Considering these insights, SiP assemblies face unique cleaning challenges.
 - Restricted access under ultra-miniature components
 - High component density, limiting spray impact and capillary action
 - Greater sensitivity to flux chemistry and process variation

For high-reliability SiP devices, it is essential to consider robust, low surface tension cleaning formulations that maintain performance across variable paste types and process settings. Process windows must be carefully optimized for chemistry concentration, spray dynamics and belt speed to ensure complete residue removal especially under challenging geometries.

FUTURE WORK

Based on the conclusions from the study, the following areas of follow-up studies has been identified. The results will be presented at a later stage.

- **Failure Mechanism Mapping Under Ultra-Miniaturized Components: Cleaning Efficiency at Higher Belt Speeds:** Conduct targeted studies using cross-sectional SEM, Ion Chromatography and localized SIR testing to identify failure initiation points under 01005 and 008004 components. Assess how partially removed flux residues evolve into conductive/corrosion spots under JEDEC-level THB conditions.
- **Residue Risk Profiling By Solder Paste and Component Geometry:** Establish a risk matrix correlating flux formulation (powder size and activator load), component size and geometry with post-cleaning residue levels and failure risks. This will help define component-specific cleaning process windows tailored for SiP applications.
- Expand the study to various solder pastes (e.g. lead-free no-clean, water soluble) to assess the universality of the conclusions.

These areas will offer valuable insights for optimizing cleaning processes, improving performance, and promoting sustainable practices when it comes to SiP assemblies.

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