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Optimizing Ultrasonic Cleaning for Flux Removal in PCBA Production

A. Din [1]*, A. Idros[2], W. K. Shyan[2], M. Y. Ali[1], Z. Zakaria[1], S. Sabikan[1] and AZ Jamil[1]

[1] *Technology Department, Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Malaysia*

[2] *L2 Department, Dominant Opto Technologies Sdn. Bhd. Melaka, Malaysia*
**Correspondence Author: A. Din (asridin@utem.edu.my)*

Abstract

Ultrasonic cleaning is a critical step in Printed Circuit Board Assembly (PCBA) manufacturing for removing flux residues and particulate contaminants that could impair long-term reliability. However, inconsistent machine setup and manual parameter adjustments often lead to incomplete cleaning, increased rework, and reduced process consistency. This study presents an optimized and standardized setting process for a PCBA ultrasonic cleaning machine, combining industrial process observations with controlled laboratory trials. Six cleaning durations (5–10 minutes) were tested at a fixed temperature of 50 °C, using quantitative flux residue measurements and visual inspection under magnification. Results showed a strong inverse correlation between cleaning duration and residual flux. The optimal performance at 10 minutes achieving 94–96% cleaning efficiency with effectively reduces flux residue on PCBAs to 4–5%. The proposed procedure offers a reproducible, operator-independent method suitable for high-volume PCBA production, supporting improved product reliability and consistent manufacturing quality.

Keywords: PCBA, ultrasonic cleaning, process optimization, flux removal, manufacturing efficiency.

Introduction

The manufacturing of Printed Circuit Board Assemblies (PCBAs) demands exceptional levels of reliability and cleanliness to ensure optimal electrical performance over the product's lifecycle. Even microscopic contamination such as solder flux residues, ionic deposits, or particulate matter can trigger corrosion, dendritic growth, and leakage currents, resulting in premature failure in service [1].

Ultrasonic cleaning, based on the principle of acoustic cavitation, is widely adopted in the electronics industry for its ability to penetrate narrow component gaps and remove embedded contaminants effectively [2].

The adoption of efficient and sustainable cleaning processes aligns directly with the United Nations Sustainable Development Goal (SDG) 9: Industry, Innovation, and Infrastructure, which promotes resilient, efficient industrial processes, and SDG 12: Responsible Consumption and Production, which encourages reduced waste generation and resource optimization. By enhancing cleaning process performance while reducing chemical and energy use, ultrasonic cleaning technology addresses both product quality and environmental sustainability targets.

Despite its benefits, ultrasonic cleaning performance is highly dependent on parameters such as cleaning duration, bath temperature, and ultrasonic power. Variations in these parameters—especially when adjusted manually by operators—can cause inconsistent cleaning quality, increased rework rates, and higher production costs [2], [3]. In high-volume manufacturing environments, this variability can negatively impact throughput, compromise product reliability, and hinder lean manufacturing objectives. While prior studies have examined flux removal chemistries and equipment designs, fewer have focused on implementing data-driven, standardized parameter settings optimized for specific PCBA types and real-world industrial contexts.

The problem addressed in this study is that, at the case study facility, the ultrasonic cleaning process lacked standardized setup parameters. Operators frequently adjusted cleaning times based on personal judgment rather than measured performance metrics, resulting in inconsistent flux removal rates, elevated particle contamination counts, and reduced equipment effectiveness. This variability increased rework and inspection times, disrupted delivery schedules, and lowered manufacturing efficiency. From an SDG 12 standpoint, these inefficiencies also translate to unnecessary resource consumption, excessive chemical use, and increased waste generation.

The objective of this research is to analyze the relationship between ultrasonic cleaning duration and flux removal efficiency for selected PCB types under controlled industrial conditions. It also aims to develop an optimized and standardized cleaning setup procedure that reduces operator dependency, and to evaluate the effect of this optimized process on production performance indicators. It including optimal performance of cleaning duration, percentage of cleaning efficiency and percentage flux residue on PCBs. By achieving these objectives, this study contributes a repeatable, evidence-based method for improving ultrasonic cleaning performance. This study also supporting both SDG 9 and SDG 12 through more efficient, cleaner, and sustainable electronics manufacturing.

Given these challenges and objectives, it is important to review recent research on ultrasonic cleaning performance, process parameter sensitivity, and data-driven optimization strategies. Such a review provides the necessary technical context for understanding how cleaning duration, frequency, and other variables influence both contaminant removal efficiency and broader manufacturing outcomes. By drawing on evidence from prior studies, this work builds a foundation for the proposed optimization approach, ensuring that the methodology is informed by proven best practices and aligned with industry trends toward higher reliability, operational efficiency, and sustainable production.

Contaminant Removal and Reliability:
Acoustic cavitation generates microscopic bubbles that collapse with high energy, dislodging flux residues and particulates even in densely populated PCBAs. Empirical results show that ultrasonically cleaned assemblies consistently exhibit lower contamination levels and more stable mechanical and electrical performance compared to uncleaned samples, supporting their adoption in high-reliability electronics [2].

Parameter Sensitivity:
Cleaning outcomes are highly sensitive to parameters such as cleaning duration, ultrasonic frequency, and bath temperature. Manual adjustments introduce variability that can reduce flux removal efficiency, elevate particle contamination, and increase rework requirements. Studies have confirmed that improper parameter control significantly impacts throughput and overall equipment effectiveness OEE [2], [3].

Standardization and Data-Driven Optimization:
Experimental design methods, such as fractional factorial analysis, have identified cleaning time and ultrasonic frequency as the most influential parameters affecting both cleaning performance and metal recovery from PCB surfaces [3]. Tailoring these parameters to specific board types enables consistent results, minimizes operator dependency, and improves process repeatability.

Sustainability and SDGs:
Process optimization not only enhances cleaning quality but also reduces the overuse of cleaning agents, water, and energy. These resource efficiencies directly support SDG 9 by promoting innovation and infrastructure improvement, and SDG 12 by advancing responsible manufacturing practices [2], [3].

Literature Review

Ultrasonic cleaning has emerged as a key technique in electronics manufacturing for the removal of solder flux residues, particulates, and other contaminants from printed circuit board assemblies (PCBAs). The process relies on the principle of acoustic cavitation, where high-frequency ultrasonic waves generate microscopic bubbles within a cleaning medium. The collapse of these bubbles' releases localized high-energy microjets, enabling penetration into tight component gaps and the dislodgement of surface contaminants without mechanical abrasion. Recent studies have demonstrated that this phenomenon is particularly effective in cleaning assemblies with complex geometries and fine-pitch components, where conventional methods are less efficient [2], [4].

The efficiency of ultrasonic cleaning is determined by a combination of mechanical, chemical, and process parameters. Mechanically, the operating frequency and power density have a significant impact on cavitation behavior and cleaning outcomes. Lower frequencies in the range of 20–40 kHz generate larger, more energetic bubbles that are effective for removing stubborn residues, whereas higher frequencies above 60 kHz create finer bubbles suited for delicate components. Optimal power density is essential to achieve sufficient cleaning force without causing microcracks, erosion, or damage to sensitive solder joints [3], [5]. Chemically, the cleaning solution's composition and operating temperature play crucial roles. Elevated temperatures lower the viscosity of the cleaning fluid and enhance detergent activity, thereby improving cavitation intensity and contaminant removal. However, excessive heating can accelerate corrosion processes or degrade heat-sensitive materials [2]. Selection of the cleaning chemistry must be aligned with the flux type—whether rosin-based, water-soluble, or no-clean—with a growing trend towards environmentally friendly aqueous solutions containing surfactants, saponifies, and chelating agents [6].

Process parameters such as cleaning time, agitation methods, and real-time process monitoring also influence cleaning performance. Extended cleaning times generally increase flux removal efficiency but risk overexposure to cavitation forces, potentially weakening fine solder joints [4]. Agitation through either mechanical stirring or pulsed ultrasonic can help maintain uniform contaminant dispersion and prevent redeposition. The integration of sensors to monitor cavitation intensity, bath temperature, and particulate concentration enables adaptive control of the process, ensuring consistent quality without over-cleaning [4].

Technological advancements have significantly improved ultrasonic cleaning performance and reliability. Developments in transducer technology, such as high-Q piezoelectric transducers and dual- or multi-frequency systems, have allowed operators to switch between aggressive and gentle cleaning modes within the same cycle. This flexibility is particularly valuable for assemblies containing both robust and sensitive components. By alternating frequency modes, shadowing effects in high-density PCB layouts can be reduced, ensuring more uniform cleaning coverage [4], [3]. Additionally, wave modulation techniques have been reported to improve cavitation distribution, enhancing residue removal in difficult-to-reach regions [5].

Environmental and safety considerations have become increasingly important in cleaning system design. The replacement of volatile organic compound (VOC)-based solvents with low-emission aqueous cleaning agents addresses both regulatory and workplace safety concerns. Recent research has shown that ultrasonication combined with green chemistry can achieve effective flux removal while reducing environmental footprint [6]. Furthermore, modern systems incorporate noise reduction enclosures, automated chemical dosing, and spill containment features to protect operators.

In terms of practical outcomes, ultrasonic cleaning has been shown to enhance the reliability of PCBAs. Controlled experiments have demonstrated that ultrasonically cleaned samples exhibit lower residual contamination levels, higher insulation resistance, and more consistent mechanical properties compared to uncleaned samples [2], [7]. These findings underscore the suitability of ultrasonic cleaning for high-reliability applications such as aerospace, medical devices, and military electronics.

Research has shown that cleaning performance can be greatly enhanced through process optimization and correct solvent usage [8], [9]. Properly tuned time and temperature improve cleaning outcomes while lowering energy usage and enabling residue removal from hard-to-reach areas [10].

Overall, the literature indicates that ultrasonic cleaning of PCBAs is a mature yet continually evolving process. Advances in frequency control, transducer design, environmentally compatible cleaning chemistries, and process monitoring systems are enabling manufacturers to achieve higher cleaning performance with reduced risk to both components and operators. This review forms the basis for the optimization framework explored in the present study.

Methodology

This study was conducted at Dominant Opto Technology Sdn. Bhd. to evaluate and optimize the setup process for ultrasonic cleaning of PCBAs, with the goal of improving flux residue removal through standardized parameter control. The methodology involved a structured study design, equipment setup, controlled experiments, and comparative data analysis.

3.1 Study Design

The experimental approach consisted of testing seven parameter settings involving fixed temperature and varying cleaning durations. Each setting was tested using the same ultrasonic cleaning system to ensure consistency. The cleaned PCBAs were then visually inspected and documented to assess flux removal efficiency.

The study was conducted at a high-volume PCBA manufacturing site. Cleaning temperature was fixed at 50°C following manufacturer recommendations, while cleaning time was varied from 5 to 10 minutes in one-minute increments (Testing Settings 1–6).

3.2 Equipment and Materials

The cleaning experiments were conducted using the Crest Powersonic P1100D Ultrasonic Cleaning Machine, 3.2 Gallons as shown in Fig.1. The machine operates with programmable time and temperature controls, and uses high-frequency ultrasonic waves to dislodge contaminants from PCB surfaces. The cleaning solution used was a standard industrial PCB cleaning detergent diluted according to manufacturer instructions. In this study the DECOTRON 356S as a water-based cleaning fluid was used as shown in Fig.2. Two PCBA samples—referred to as PCB A and PCB B—were used for pre- and post-cleaning evaluation.

Fig.1 Ultrasonic cleaning machine

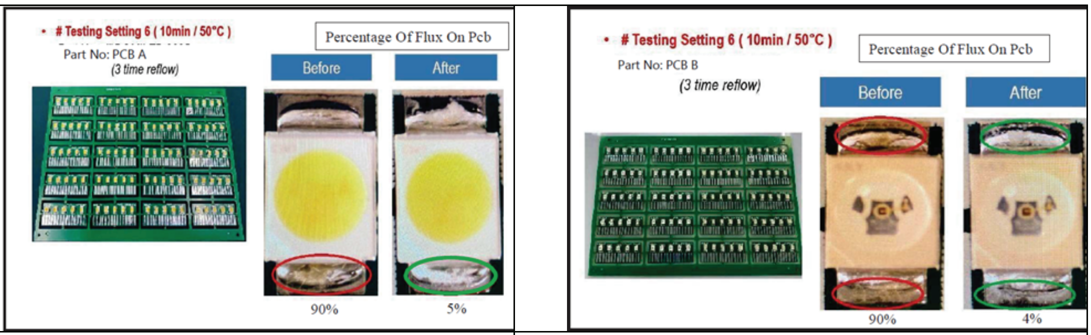
Fig.2 Cleaning fluid

3.3 Parameter Settings

The cleaning temperature was consistently maintained at 50°C for all experimental trials, in accordance with manufacturer guidelines and industry standards. The cleaning time was varied across six distinct durations—5, 6, 7, 8, 9, and 10 minutes—corresponding to Testing Settings 1 through 6, respectively. After each ultrasonic cleaning cycle, the PCB samples underwent a standard rinsing process followed by air drying to complete the procedure.

3.4 Data Collection

Visual inspection was conducted on both PCB A and PCB B before and after cleaning, using a 10x magnification illuminated desktop microscope. High-resolution photographs were captured and used as comparative evidence of cleanliness. Fig.3 shows the examples of the photographs.



(a) (b)

Fig.3 Visual Comparison of Flux Residue on PCB A (a) and PCB B (b) Before and After Ultrasonic Cleaning at Testing Setting 6 (10 Minutes / 50°C).

3.5 Analytical Techniques

The evaluation of cleaning effectiveness was primarily based on visual inspection and supported by quantitative assessment of flux residue. To estimate the amount of flux residue, the following formula was used:

Percentage of Flux = (Weight of Flux / Weight of Total Solder Paste) x 100%

In addition to measuring the percentage of flux present, the cleaning efficiency was calculated to determine the proportion of flux residue removed relative to the initial contamination level. This metric provides a clearer indication of the process effectiveness across different cleaning durations and PCB types. The efficiency of cleaning calculation used the following formula:

Cleaning Efficiency= (% Initial Residue- % Final Residue) / (% Initial Residue) x 100%

3.6 Reproducibility Assurance and Process Control

All tests were conducted under identical environmental conditions and repeated to confirm consistency. Operators followed a standardized setup and cleaning protocol, including consistent chemical concentrations and rinse durations. To ensure reproducibility, all trials were conducted under identical environmental conditions, using a standard rinse (90 s DI water) and air-dry procedure.

Results and Discussion

The results of this study are presented and analyzed to provide a comprehensive understanding of the relationship between ultrasonic cleaning duration and flux removal performance in PCBA manufacturing. This section begins with a quantitative baseline assessment derived from tabulated flux residue percentages and calculated cleaning efficiencies (subsection 4.2), followed by a visual trend analysis using line chart representations to highlight performance patterns over time (subsection 4.3). The discussion then addresses the limitations of the study (subsection 4.4) to contextualize the findings within practical industrial constraints. Subsequently, the implications of these results for manufacturing practice are explored, along with recommendations for process optimization (subsection 4.5). Finally, potential directions for future research are proposed (subsection 4.6) to encourage further advancements in ultrasonic cleaning technology and its application in high-reliability electronics production.

4.1 Overview of Findings

The ultrasonic cleaning effectiveness was evaluated across six different testing settings, with fixed flux presence (90%) and cleaning temperature (50°C), while varying the cleaning time. Quantitative data was collected for both PCB A and PCB B, and tabulated in Table 1.

Table 1 Flux Residue Percentage and Ultrasonic Cleaning Efficiency for PCB A and PCB B Across Six Time-Based Testing Settings (5–10 Minutes)

Testing Setting	Flux Remaining (PCB A)	Efficiency (PCB A)	Flux Remaining (PCB B)	Efficiency (PCB B)
1	48%	47%	55%	39%
2	41%	54%	46%	49%
3	33%	63%	36%	60%
4	25%	72%	25%	72%
5	15%	83%	15%	83%
6	5%	94%	4%	96%

4.2 Quantitative Baseline (Table Analysis)

Table 1 presents the numerical progression of flux residue percentages and corresponding cleaning efficiencies for both PCB A and PCB B across six time-based settings. At shorter times (5–6 minutes), residue percentages remain relatively high—48–41% for PCB A and 55–46% for PCB B—indicating incomplete flux removal. Corresponding efficiencies range from 47% to 54% for PCB A and 39% to 49% for PCB B, suggesting that cleaning action is insufficient to address deeper or more adherent residues.

In the mid-range settings (7–9 minutes), efficiency improves more markedly, with reductions in flux residue of approximately 8–10 percentage points per minute for both boards. This improvement aligns with the sustained acoustic cavitation effects capable of penetrating fine-pitch component gaps. Interestingly, PCB B shows a steeper rise in efficiency between 7 and 9 minutes, possibly due to differences in flux residue composition or surface geometry.

By Setting 6 (10 minutes), both PCB types achieve high cleanliness, with final residues of 5% (PCB A) and 4% (PCB B), corresponding to efficiencies of 94% and 96%, respectively. These values indicate that a 10-minute cleaning time at 50 °C is optimal under the tested conditions, with further extension unlikely to produce significant benefits.

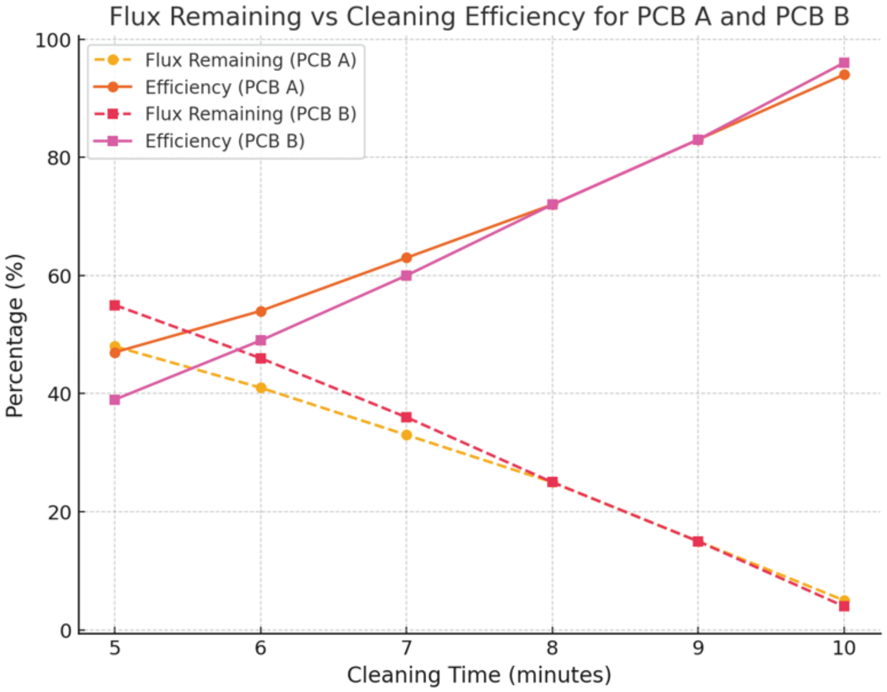


Fig. 4 Flux residue percentage and ultrasonic cleaning efficiency for PCB A and PCB B as a function of cleaning time (5–10 minutes).

4.3 Visual Trend Analysis (Line Chart Interpretation)

The line chart in Fig. 4 representation of the data reinforces the time–performance correlation observed in Table 1. Both PCBs display a strong inverse relationship between flux residue and cleaning efficiency. Efficiency curves for both boards rise steadily with cleaning time, while residue curves decline at a nearly symmetrical rate.

The parallel slope patterns for PCB A and PCB B suggest that the process dynamics—driven by ultrasonic cavitation—are consistent across different board designs. The steeper efficiency gains between 7 and 9 minutes for PCB B is visually distinct, indicating that certain board types may benefit disproportionately from additional cleaning exposure.

The graphical trend also highlights the diminishing returns near the 10-minute mark, where efficiency gains flatten. This stage suggests that beyond 94–96% removal efficiency, further residue reduction may require alternative process adjustments, such as chemistry changes or multi-frequency cleaning, rather than additional time.

4.4 Limitations

Although the study includes a quantitative flux percentage formula, it lacks chemical-level contamination testing such as Fourier transform infrared spectroscopy (FTIR) or ion chromatography. The calculated values are based on estimations, not direct instrument measurements, limiting microscopic accuracy.

4.5 Implications and Recommendations

The data suggests that 10 minutes at 50°C is optimal for effective ultrasonic cleaning of flux on medium-density PCBs. This finding is critical for standardizing setup parameters in industrial environments, reducing manual error, and improving process repeatability.

4.6 Future Research Directions

Future studies should include ionic contamination testing, assess various flux types and PCB designs, and explore advanced ultrasonic methods. Investigating multi-stage or variable-frequency cleaning and smart monitoring systems is also recommended.

Conclusion

This study demonstrated that ultrasonic cleaning performance in PCBA manufacturing is strongly influenced by cleaning duration, with a clear inverse relationship between flux residue and cleaning efficiency. Experimental results showed that extending cleaning time from 5 to 10 minutes progressively improved flux removal, culminating in efficiencies exceeding 94% for both PCB types at the optimal 10-minute cycle. The findings highlight the importance of standardized, data-driven parameter settings to minimize operator dependency, ensure consistent cleaning quality, and enhance product reliability. While the study was conducted under controlled industrial conditions with a fixed temperature and chemistry, the results provide a replicable framework for process optimization in similar manufacturing contexts. Future work should explore the combined effects of ultrasonic frequency, temperature, and cleaning chemistry to further improve cleaning performance. Such investigations should also aim to reduce energy and resource consumption, thereby supporting both operational excellence and the United Nations' Sustainable Development Goals (SDG 9: Industry, Innovation, and Infrastructure; SDG 12: Responsible Consumption and Production).

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References

[1] S. Wakeel, A. Haseeb, M. Afifi, S. Bingöl, and K. L. Hoon, "Constituents and performance of no-clean flux for electronic solder," Microelectronics Reliability, vol. 123, p. 114177, 2021. doi: 10.1016/J.MICROREL.2021.114177.

[2] Z. Plachý, T. Hurtony, A. Géczy, and K. Dušek, "Board level underfill – the influence of flux," in 2023 46th Int. Spring Seminar on Electronics Technology (ISSE), 2023, doi: 10.1109/ISSE57496.2023.10168355.

[3] R. Dikamdima, S. Ismail, K. Ishak, and S. Hashim, "Fractional factorial design of ultrasonic-assisted metal recovery from waste printed circuit board," J.

Mater. Cycles Waste Manag., 2023, doi: 10.1007/s10163-023-01869-4.

[4] B. Jacobson et al., “A mechanistic study identifying improved technology critical metal delamination from printed circuit boards at lower power sonications in a deep eutectic solvent,” Ultrasonics Sonochemistry, vol. 101, 2023, doi: 10.1016/j.ultsonch.2023.106701.

[5] C. Chu, T. Lu, and Y. Fuh, “The suitability of ultrasonic and megasonic cleaning of nanoscale patterns in ammonia hydroxide solutions for particle removal and feature damage,” Semicond. Sci. Technol., vol. 35, 2020, doi: 10.1088/1361-6641/ab675d.

[6] P. Jadhao, E. Ahmad, K. Pant, and K. Nigam, “Environmentally friendly approach for the recovery of metallic fraction from waste printed circuit boards using pyrolysis and ultrasonication,” Waste Manag., vol. 118, 2020, doi: 10.1016/j.wasman.2020.08.028.

[7] R. Jha, R. Sharma, M. Agrawal, M. Rao, and K. Singh, “Exploring the pretreatment routes of waste printed circuit boards for enhanced metal recovery,” Mater. Today: Proc., 2023, doi: 10.1016/j.matpr.2023.08.006.

[8] G. J. Abarro, V. Aguinaldo, A. Ceasar-Paule, A. Tan, and M. S. Ramos, “Qualitative & quantitative study of flux-clean solution for smart high-side device,” 2017 IEEE 19th Electronics Packaging Technology Conference (EPTC), pp. 1–5, 2017. doi: 10.1109/EPTC.2017.8277480.

[9] C. Hecht et al., “Laser Cleaning of Flux Residues on Copper Surfaces in Electronics Production,” 2022 IEEE 28th International Symposium for Design and Technology in Electronic Packaging (SIITME), pp. 65–69, 2022. doi: 10.1109/SIITME56728.2022.9987997.

[10] A. Hsieh et al., “The effect and application of low VOC automatic cleaning process,” 2023 18th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT), pp. 111–113, 2023. doi: 10.1109/IMPACT59481.2023.10348894.