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Optimization of Silver Electroplating Parameters for Lead Frame Thickness Using Design of Experiment (DOE)

Hamzatul Hanim Husin, Jafri Mohd Rohani and Nurul Rawaida Ain Burhani
Faculty of Mechanical Engineering
Universiti Teknologi Malaysia (UTM)
81300 Skudai, Johor Malaysia
hanimhusin@gmail.com, jafrimr@utm.my, nurulrawaidaain@utm.my

Abstract

The increasing demand in the semiconductor industry highlights the crucial role of lead frames in electronic components. Among various manufacturing techniques, silver electroplating is a key process to ensure optimal performance and reliability of lead frames. This study investigates the influence of electroplating parameters on coating thickness by applying the design of experiment (DOE) methodology. The main objectives are to identify and validate the key electroplating parameters that influence silver coating thickness and to quantify their effects. A combination of Hull cell tests, DOE and analysis of variance (ANOVA) were used to evaluate the importance of parameters such as current density, plating time, silver concentration and plating temperature. The results show that current density and plating time are the most important factors affecting the coating thickness, as shown by their high F values and p values less than 0.05. While silver concentration and plating temperature also have an influence on layer thickness, their influence is comparatively less significant. This study establishes a clear relationship between electroplating parameters and coating thickness and provides valuable insights for process optimization in silver electroplating, which can improve the quality and efficiency of lead frame production.

Keywords
Electroplating, Design of Experiment (DOE), ANOVA, Electroplating parameters

1. Introduction
The semiconductor industry is critical to modern technology and influences a wide range of applications including consumer electronics, medical devices, automotive systems and home appliances. As demand for electronic devices continues to rise, the global semiconductor market is expected to witness steady growth, driven by advancements in technologies such as 5G networks, artificial intelligence (AI), the Internet of Things (IoT), and electric vehicles (EVs), Healthcare, Defense, Transportation and Renewable Energy (Global Semiconductor Lead Frame Market 2024-2032). Lead frames are a crucial component in the semiconductor package. They represent the electrical interface between the silicon chip and external connections and thus ensure reliable signal transmission. Lead frames are typically made from thin metals such as copper, iron, nickel or copper alloys and usually undergo galvanic processes. Electroplating involves depositing a thin layer of conductive metal such as silver, gold, palladium or nickel on the surface of the lead frame. This process uses electrochemical ionization, in which an electrolyte solution and electrical current drive metal deposition (Gamburg & Zangari, 2011). The main objective of electroplating in lead frame manufacturing is to provide corrosion resistance, maintain a smooth surface finish, and achieve uniform coating thickness, all of which are essential for reliable wire bonding, forming, and soldering processes.

However, quality issues during the electroplating process, particularly variations in coating thickness, have led to increased customer complaints. The thickness of the coating is influenced by a number of plating parameters, including current density, plating time, electrolyte composition, and the geometry of the plating surface (Schlesinger &

Paunovic, 2010). Accurately achieving the desired coating thickness is critical as any deviation can affect the electrical performance and longevity of the final device. It is therefore crucial to identify and optimize the process parameters in order to consistently meet the targets. To address these challenges, the Design of Experiment (DOE) methodology offers a structured approach to identifying optimal process parameters. DOE enables systematic experimentation, analysis, and optimization, providing a powerful tool to improve process performance, reduce variability, and minimize operational costs (Montgomery, 2013). This method is particularly valuable when it comes to ensuring that manufacturing processes meet customer specifications, allowing manufacturers to optimize efficiency, reduce waste, and maintain cost effectiveness. Identifying the key parameters that control plating performance is therefore critical to improving both the quality and reliability of semiconductor packaging.

1.1 Objectives

The aim of this research is to identify and analyze the electroplating parameters that affect coating thickness, determine the key factors affecting coating thickness, and validate the relationship between these significant parameters and the resulting thickness.

2. Literature Review

Electrodeposition is a key process for depositing metal or semiconductor coatings on conductive substrates, driven by an electric current passing through an electrolyte containing metal or semiconductor ions. This electrochemical process requires external current due to the positive free energy change associated with the deposition reaction, preventing it from occurring spontaneously (Ojo and Dharmadasa 2018). The quality and uniformity of electroplating coatings is highly dependent on several factors including electrolyte composition, pH, temperature, current density and electroplating time (Ojo and Dharmadasa, 2018). These parameters must be precisely controlled to ensure desired coating properties, including uniform thickness, adhesion and corrosion resistance. Recent studies have highlighted the crucial role of optimizing the interaction between process parameters. Siah et al. (2019) identified that uniform electrodeposition is achieved by controlling the electroplating bath concentration, current density, and anode material. However, the relationship between current density and bath concentration is crucial because higher current densities require higher electrolyte concentrations to maintain current efficiency. Their study found that optimal conditions are 70-75 g/L potassium argent cyanide and a current density in the range of 1-2 A/dm^2. However, the potential trade-offs between high current efficiency and coating uniformity, especially at higher current densities, remain poorly understood. Schlesinger and Paunovic (2006) emphasized that current density distribution is a primary factor affecting coating thickness. Their 2010 work extended this by considering the effects of plating time, electrolyte composition, and substrate geometry, and showed that these factors work together to influence coating thickness uniformity (Paunovic et al. 2010). Permana et al. (2021) disclosed that to achieve a minimum thickness of 40 microns, the electroplating time must be set to 5 minutes, with an electrolyte density of 22 Baume, a voltage of 5 V and a maximum surface area of 415 cm^2. Although these parameters are clearly defined, their interactions and potential for variation in real applications require further clarification. Izamshah et al. (2002) found that coating thickness uniformity is highly dependent on current and coating speed, with optimal conditions found to be 120 A and 3.46 m/min, respectively.

Although these parameters are optimal at controlled settings, they may not take into account the variability in industrial-scale production, where factors such as material variability, surface roughness and process variations influence the final coating quality. Similarly, Rose and Whittington (2002) emphasized the importance of current density control to ensure uniform deposition. However, their study did not address how these results impact industrial environments where real-time adjustments and process stability are essential for consistent quality. Le et al. (2015) proved that while increasing current density increases plating thickness, it also introduces defects such as surface porosity and internal structure voids at higher densities. Their study identified an optimal range of 10-20 mA/cm^2 for current density, $CuSO_4$ concentration of 0.4 mol/L, and H_2SO_4 concentration of 1.0 mol/L to achieve uniform plating. However, their focus on lower current densities limits its applicability to high-throughput industrial processes, where higher current densities are necessary to achieve faster deposition rates. While these studies provide valuable insights into the factors influencing electroplating, they often focus on idealized laboratory conditions. Industrial electroplating processes are more complex, involving variability in material properties, dynamic process control, and scale-up challenges. Therefore, further research is needed to develop more comprehensive models that account for these complexities. Understanding the interactions between key process parameters under real-world conditions is essential for optimizing electroplating processes to achieve high efficiency, uniform coating thickness, and defect-free performance in industrial applications.

3. Methods

A 2 × 3 factorial design of experiment was employed to investigate the influence of electroplating parameters on plating thickness. The experimental factors, including silver bath concentration, current density, plating temperature, and plating time, were varied at two or three levels, as outlined in Table 3.1. The Hull Cell Test as in Figure 3.1 was used to evaluate the effects of these parameters on the plating process. The primary response variable, plating thickness, was measured using X-ray fluorescence (XRF) to ensure precise and non-destructive thickness assessment. Data analysis was performed using MINITAB software to conduct Analysis of Variance (ANOVA) and identify significant factors influencing plating thickness.

Table 1: Factor Levels for Experimental Design

Factor	Low (-1)	High (+1)
Siler bath concentration (g/L)	25	35
Current density (ASD)	2	5
Plating temperature (°C)	30	50
Plating time (min)	2	4

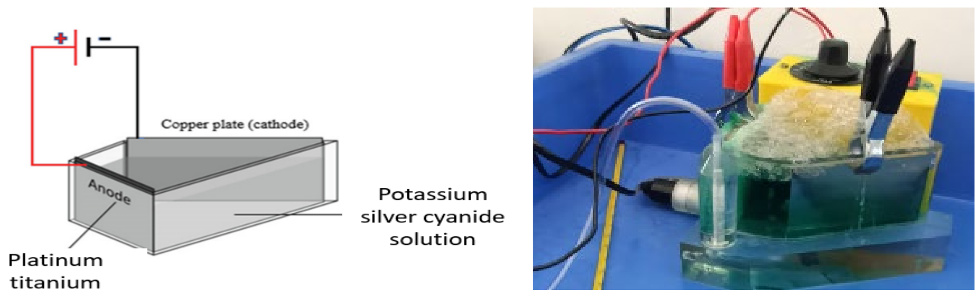

Figure 1: Hull Cell Test Experimental setup

4. Data Analysis

The data from the Design of Experiments (DOE) were analyzed using MINITAB software, with Analysis of Variance (ANOVA) performed to assess the significance of each factor on plating thickness. The factors studied were silver bath concentration (A), current density (B), plating temperature (C), and plating time (D). The ANOVA results, shown in Table 4.2, identified significant main effects, two-way interactions (e.g., A×B, B×D), three-way interactions (e.g., A×B×C), and a four-way interaction (A×B×C×D). The error term captures unsolved variability, while the total variance reflects the combined influence of the factors and their interactions on plating thickness.

Table 2: ANOVA Analysis

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	15	1078538	71903	299.26	0.000
Linear	4	1038787	259697	1080.87	0.000
A	1	1979	1979	8.24	0.007
B	1	510056	510056	2122.89	0.000
C	1	15045	15045	62.62	0.000
D	1	511707	511707	2129.76	0.000
2-Way Interactions	6	37986	6331	26.35	0.000
A*B	1	626	626	2.61	0.116
A*C	1	0	0	0.00	0.997
A*D	1	882	882	3.67	0.064
B*C	1	90	90	0.38	0.544
B*D	1	35491	35491	147.71	0.000
C*D	1	896	896	3.73	0.062
3-Way Interactions	4	1765	441	1.84	0.146
A*B*C	1	830	830	3.45	0.072
A*B*D	1	135	135	0.56	0.458
A*C*D	1	784	784	3.26	0.080
B*C*D	1	15	15	0.06	0.803
4-Way Interactions	1	1	1	0.00	0.953
A*B*C*D	1	1	1	0.00	0.953
Error	32	7688	240		
Total	47	1086227			

5. Results and Discussion

5.1 Result Analysis

The results from the ANOVA analysis indicate that the overall model is statistically significant, with a p-value of 0.000. All individual factors: silver bath concentration (A), current density (B), plating temperature (C), and plating time (D), show p-values less than 0.05, confirming that each factor significantly influences silver-plating thickness. Among these, current density (B) exhibits the strongest effect, as reflected by the highest F-value, followed by plating time (D), plating temperature (C), and silver bath concentration (A).

The Pareto chart generated by MINITAB (Figure 5.1) further illustrates the relative impact of these factors. The analysis was conducted with a significance level of α=0.05, where the red vertical line marks the threshold for statistical significance (set at 2.04 standardized effect units). Factors with bars extending beyond this line are considered to have a major influence on the plating thickness. The Pareto chart shows that plating time (D) has the largest effect on plating thickness, with current density (B) also having a significant, though slightly lesser, impact. Plating temperature (C) was found to be significant, but its influence is smaller compared to plating time and current density. Silver bath concentration (A), while statistically significant, had the least impact among the four factors. These findings are consistent with the ANOVA results presented in Table 4.2.

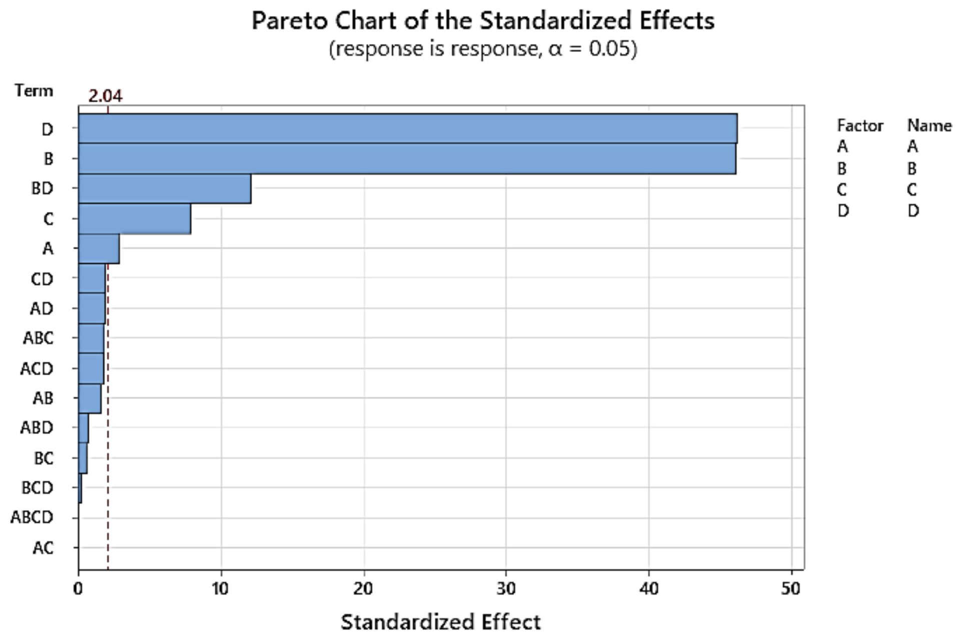

Figure 2: MINITAB Pareto Chart of Factors Influencing Silver-Plating Thickness.

The interaction between factors B (current density) and D (plating time) was highly significant, suggesting that their combined effect on plating thickness is more significant than the individual effects of each factor. Additionally, the three-way interaction between factors B, C, and D was found to be significant, indicating that the interaction between these three factors also influences the response. Therefore, the factors B, C, D and their interactions (particularly BD and BCD) should be carefully controlled and optimized to achieve the desired plating thickness. Based on the ANOVA, current density (B) and plating time (D) are the most influential positive factors on plating thickness. When both are set to high levels (+1), the plating thickness reaches its maximum, as confirmed by the Main Effects Plot (Figure 5.2).

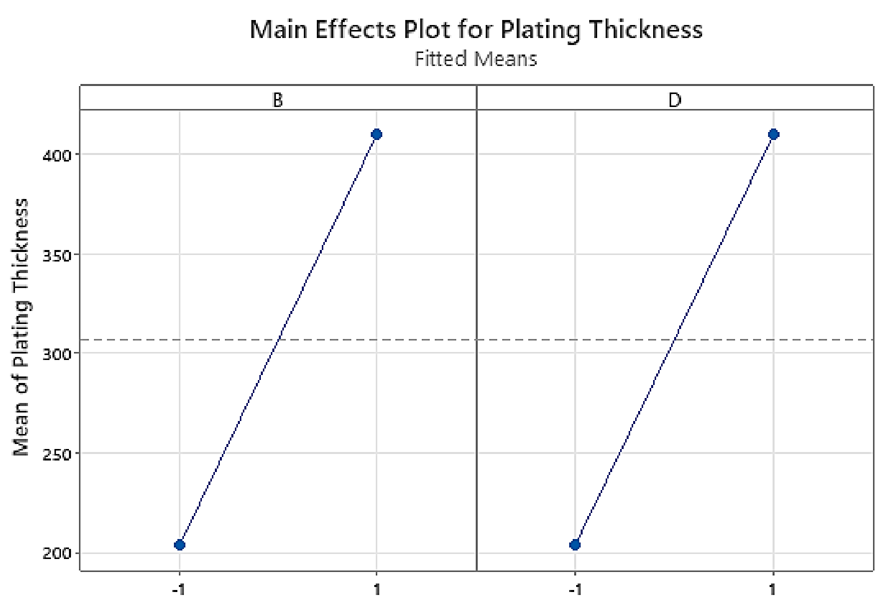

Figure 3: MINITAB Main Effects Plot for Plating Thickness vs. Significant Factors.

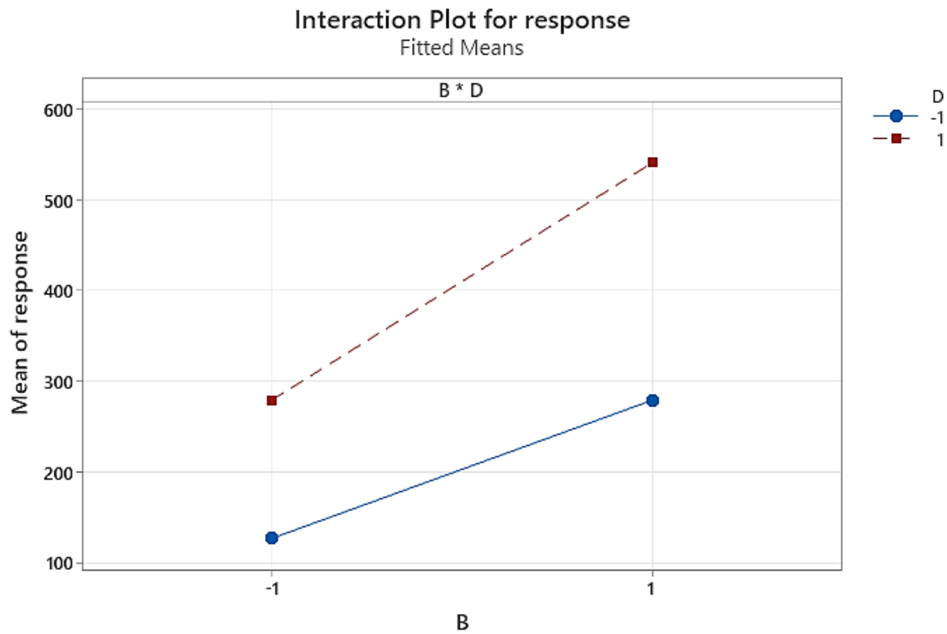

Figure 4: MINITAB Interaction Plot for Mean of response for current density (B) and plating time (D).

The interaction between current density (B) and plating time (D) reveals a significant combined effect on the silver-plating thickness, as indicated in Figure 3. Both factors independently contribute to an increase in plating thickness, but their interaction results in a compounded effect, where high levels of both current density and plating time yield significantly greater plating thickness than the sum of their individual contributions. This positive interaction suggests that the effects of B and D are not independent, and optimizing these parameters concurrently is essential to achieve the desired plating thickness. The strong interaction between these factors highlights the importance of their simultaneous optimization in electroplating processes since neglecting one factor while adjusting the other could lead to suboptimal electroplating results. Furthermore, the findings highlight the need to consider factor interactions in experimental designs to ensure precise control over plating quality and thickness.
The model's ability to predict the plating thickness with a high degree of accuracy further emphasizes the practical applicability of these insights in industrial electroplating processes. Based on the factor coefficients, a regression model was developed as in Equation 1 below:

$$y = 306.83 + 103.25B + 103.08D \qquad \text{(Equation 1)}$$

Where; y is the silver-plating thickness (µm), B is the current density (ASD), and D is the plating time (min). The positive interaction between B (current density) and D (plating time) as shown in the regression model implies that both factors jointly influence the plating thickness. The combination of high current density and long plating time results in a greater plating thickness, more than the individual contributions of these factors. Understanding and optimizing this interaction are crucial for the electroplating process to achieve uniform and consistent results.

5.2 Result Validation
To validate the regression model, confirmation runs were performed using the significant factors, current density (B) and plating time (D), at their high levels. Four trial runs were conducted under these conditions, with results presented in Table 3. The average plating thickness from the confirmation runs was 547.18 µm, while the predicted value from the regression model for the same conditions was 513.17 µm. This results in a percentage error of 6.62%, which is within the generally accepted tolerance of less than 10%. This deviation suggests that while the model performs well, there may be additional factors not accounted for or inherent variability within the experimental process.

5.3 Discussion
The analysis of the Design of Experiment (DOE) reveals that all investigated factors; silver bath concentration, current density, plating temperature, and plating time, have statistically significant effects on plating thickness. These findings

corroborate previous studies that demonstrate a direct relationship between higher current densities and increased plating thickness, driven by enhanced deposition rates. The results indicate that current density significantly accelerates the deposition process, leading to thicker silver layers. Similarly, extended plating times are directly associated with increased plating thickness, reinforcing the dual importance of current density and plating time in controlling the electroplating process.

The optimization of both current density and plating time is crucial to achieve a balance between deposition rate, layer thickness, and electrical resistivity, as noted by Lin and Lin (2004). Bayramoğlu et al. (2008) further confirmed that increased current density correlates with thicker plating, although excessive current density can lead to adverse effects, such as poor uniformity and defects. This observation contrasts with theoretical expectations based on Faraday's Law, which suggests that mass deposition should be linearly proportional to current density. The results of this study suggest that while higher current densities enhance deposition rates, they must be paired with optimal electrolyte concentrations to maximize plating quality. This aligns with findings from Izamshah et al. (2022), who distinguished that increasing electrolyte concentration improves current efficiency up to a certain threshold.

Interestingly, in this study, silver bath concentration was not a dominant factor influencing plating thickness. This discrepancy may arise from the operating conditions of the existing production line, where silver bath concentrations were not varied beyond typical levels. Under these conditions, variations in bath concentration did not exhibit significant effects on plating thickness, which contrasts with the findings of previous studies that identified concentration as a critical parameter in electroplating (Le et al., 2015).

5.4 Recommendations for Industry Application

Based on the results of this study, several key recommendations are proposed to optimize the electroplating process and improve operational performance. They are; wider range of silver bath concentrations, use of advanced characterization techniques, real-world validation in production environments and comparative analysis with alternative plating methods. It is recommended that future DOE experiments examine a broader range of silver bath concentrations, including extremely high and low values. This would enable a more comprehensive understanding of the influence of electrolyte concentration on coating thickness and current efficiency. Furthermore, implementing a three-level approach (low, medium, high) for each factor would allow a more detailed understanding of its effects under different operating conditions. To better assess the microstructure and quality of the plated layers, it is recommended to use advanced analytical techniques such as scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX). These methods will provide valuable insights into the surface morphology, uniformity and elemental composition of the electroplated layers and enable a deeper understanding of the factors that contribute to the quality of the coating. Future research should focus on conducting experiments in production environments to evaluate additional performance metrics such as adhesion strength, solderability, and wire bonding reliability. These factors are critical to the functional performance of electroplated components in end applications, particularly in high-performance sectors such as automotive electronics and telecommunications. A more comprehensive comparative study using different electroplating processes and materials (such as gold, palladium or copper) could provide valuable insights into the applicability of the optimization strategies identified in this study (Zhang et al. 2023). This would facilitate the development of universally applicable electroplating techniques and enable the industry to adopt the most effective strategies for specific applications.

6. Conclusion

In conclusion, this study successfully achieved its primary objectives: to identify and validate the coating parameters that affect silver coating thickness in the lead frame manufacturing process at ABC Manufacturing. By applying Design of Experiment (DOE), it was found that silver bath concentration, current density, plating bath temperature and plating time have a significant influence on plating thickness. Current density and coating time were identified as the most influential parameters, with a high proportion of both factors contributing to increased layer thickness. The ANOVA analysis and Pareto chart confirmed the statistical significance of these factors, while the regression model validated through confirmation runs provided a reliable prediction of coating thickness with an acceptable percentage error. These results support the practical application of focusing on current density and plating time to achieve more consistent and higher quality plating results. The results also highlight the importance of understanding the interactions between these and other factors in the electroplating process. By leveraging this knowledge, ABC Manufacturing can improve quality control, optimize production efficiency, and reduce variability, thereby improving overall operational performance. In terms of objectives, this study highlights the utility of DOE in optimizing key electroplating parameters, ensuring high-quality electroplating results and strengthening the company's competitive advantage in the manufacturing sector.

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Biographies

Hamzatul Hanim Husin is a Master of Science (Industrial Engineering) student at Universiti Teknologi Malaysia, Johor, Malaysia. She has 14 years of experience as a Quality Engineer and is currently working in a Semiconductor Factory at Pasir Gudang, Johor Malaysia. Her job scope includes in-process quality control, process improvement, auditing, and statistical process control (SPC). She decided to pursue a Master's degree to deepen her knowledge and technical expertise in Quality Engineering.

Jafri Mohd Rohani is an Associate Professor at the Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM), with over 30 years of experience teaching industrial engineering courses. He holds a PhD from UTM (2014), an MSc in Industrial Systems Engineering from Ohio University (1995), and a BSc in Industrial Engineering from New Mexico State University (1988). He has supervised numerous PhD and Master's students and is active in research, with over 22 Web of Science and 10 Scopus-indexed journal articles, a research book, and two book chapters. He has secured more than RM 1 million in research funding and consultancy projects. His scholarly work has earned him an h-index of 14 on Scopus and 19 on Google Scholar, with over 1,747 citations. Dr. Rohani has been invited as a keynote speaker at international conferences and serves on editorial boards and technical committees for various journals and conferences. Additionally, he consults for NIOSH Malaysia and DOSH on occupational safety and health projects and coordinates several MOUs with institutions such as NIOSH Malaysia and Universitas Sebelas Maret, Surakarta.

Nurul Rawaida Ain Burhani is a Senior Lecturer at the Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM) specializing in reliability and the engineering application of Artificial Intelligence. She holds a PhD in Mechanical Engineering from Universiti Teknologi Petronas and has extensive teaching experience in various engineering disciplines. She has been recognized with multiple awards, including the QIU Innovative Teaching and Learning Award and the Best Paper Presentation at flagship conference. She has secured significant research grants and has contributed to various research publications on predictive maintenance. In addition to her academic role, she actively participates in NGOs: YOSH MyFundAction and National STEM Association, youth development programs, and STEM initiatives. She has also been a reviewer for prestigious journals and conferences and has been invited to share her expertise as a speaker and trainer in various academic and professional settings worldwide.