# PERINCIAN DAN KEBOLEHHARAPAN SAMBUNGAN PATERI SAC305 KOMPONEN BGA DENGAN PENGGUNAAN DUA JENIS PEMINDAHAN HABA UNTUK KAEDAH PROSES KERJA SEMULA

ADLIL AIZAT BIN ISMAIL



UNIVERSITI KEBANGSAAN MALAYSIA

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TESIS YANG DIKEMUKAKAN UNTUK MEMPEROLEH
IJAZAH DOKTOR FALSAFAH

INSTITUT KEJURUTERAAN MIKRO DAN NANOELEKTRONIK
UNIVERSITI KEBANGSAAN MALAYSIA
BANGI

2026

UNIVERSITI KEBANGSAAN MALAYSIA
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**PENGAKUAN**

Saya akui karya ini adalah hasil kerja saya sendiri kecuali nukilan dan ringkasan yang tiap-tiap satunya telah saya jelaskan sumbernya.

16 Januari 2026

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## PENGHARGAAN

Syukur alhamdulillah ke hadrat Allah S.W.T. kerana dengan limpah rahmat-Nya saya telah dapat menyempurnakan tesis ini. Saya merakamkan setinggi-tinggi penghargaan dan terima kasih kepada penyelia utama saya, Dr. Maria Abu Bakar, serta ketua projek TAP-K022551, Prof. Dr. Azman Jalar, atas bimbingan ilmiah, dorongan berterusan dan keprihatinan mereka sepanjang perjalanan penyelidikan ini. Jutaan terima kasih turut saya hulurkan kepada SanDisk Storage Malaysia Sdn. Bhd. dan Universiti Kebangsaan Malaysia di atas sokongan kewangan melalui geran penyelidikan TAP-K022551. Penghargaan khas juga ditujukan kepada Jabatan *Package Technology Development & Integration* dan *Rework System Development* atas sumbangan bahan penyelidikan, serta kesudian menjayakan kerjasama projek ini.

Saya amat berterima kasih kepada pengurus saya, Erwan Basiron, para rakan sekerja, serta seluruh warga kumpulan penyelidikan Pempakejan Mikroelektronik dan Bahan (MIPAC) yang telah banyak membantu, berkongsi ilmu dan memberi galakan sepanjang tempoh pengajian. Sokongan kalian sangat bermakna dalam mencapai kejayaan ini.

Penghargaan paling istimewa dipersembahkan kepada isteri tersayang, Nur Amelia Aryani Hashim, serta dua permata hati kami, Amir Aqil dan Aira Amira. Kesabaran, pengorbanan dan motivasi berterusan daripada kalian menjadi sumber kekuatan utama saya. Tidak dilupakan juga kepada abah, Ismail Ali, mama, Siti Mahpuzah Hamid, bapa mentua, Hashim Chik dan ibu mentua, Roszana Abd Halim yang sentiasa mendoakan, memberi dorongan dan sokongan tanpa henti; serta seluruh ahli keluarga yang sentiasa berada di sisi. Semoga Allah S.W.T. membalas segala jasa dan kebaikan semua pihak yang terlibat secara langsung mahupun tidak langsung dalam menyempurnakan tesis ini.

Sekian, terima kasih. Wassalam.

**ABSTRAK**

Tesis ini membentangkan kajian komprehensif ke atas pencirian dan kebolehharapan sambungan pateri SAC305 komponen tatasusunan grid bebola (BGA) tertakluk kepada kaedah proses kerja semula menggunakan dua mekanisme pemindahan haba yang berbeza, pemanasan olakan dalam kerja semula udara panas dan pemanasan sinaran dalam kerja semula laser di bawah keadaan kitaran haba terpecut. Aloi pateri SAC305 telah digunakan pada papan litar bercetak (PCB) pengawet kebolehpematerian organik (OSP) dan ujian kitaran haba (TCT) dilakukan sehingga 900 kitaran untuk mereplikakan keadaan kendalian. Analisis perbandingan menunjukkan bahawa kerja semula laser menghasilkan tegasan haba yang jauh lebih rendah daripada kerja semula udara panas dan mengurangkan kerosakan mekanikal pada sambungan pateri komponen bersebelahan. Taksiran pasca TCT menggunakan ujian pencelup dan tarikan (DnP) mendedahkan bahawa sampel kerja semula laser masing-masing mempunyai 3.33% dan 13.73% kurang kerosakan berbanding sampel kerja semula udara panas di bawah keadaan sebelum dan selepas TCT. Untuk memahami lebih lanjut tentang mekanisme kegagalan umum pada sambungan pateri komponen BGA, kajian ini menggabungkan analisis ketumpatan tenaga terikan (SED) untuk mengenal pasti kawasan yang berkemungkinan berlaku retakan. Keputusan simulasi menunjukkan bahawa nilai SED tertinggi, sehingga 3.4048 Pa, berada di penjuru pakej BGA, manakala nilai terendah, sekitar 0.01803 Pa, ditemui di tengah. Pengagihan ini membantu mencari kawasan yang mempunyai tegasan, yang mana retakan mungkin bermula. Peta kontur SED membolehkan perbandingan antara lokasi kegagalan simulasi dan sebenar dengan nilai SED tertinggi menunjukkan tapak kemungkinan kegagalan sambungan pateri bermula. Kaedah ini meningkatkan pemahaman tentang tingkah laku kegagalan dan menyokong reka bentuk dan strategi kerja semula yang lebih dipercayai untuk pemasangan elektronik berketumpatan tinggi. Tambahan pula, tesis ini meneroka kesan proses kerja semula dan penuaan haba pada pembentukan sebatian antara logam (IMC) pada antara muka substrat BGA dan PCB. Pencerapan pada komponen kerja semula (U123) dan bersebelahan (U129) menunjukkan bahawa kerja semula udara panas mendorong pembentukan IMC yang seragam tetapi meluas melalui taburan haba, manakala kerja semula laser menghasilkan corak pertumbuhan yang lebih setempat dan pelbagai, terutamanya pada antara muka substrat PCB. Berdasarkan penemuan ini, kajian ini membentangkan pendekatan rangkaian neural buatan (ANN) novel untuk meramalkan pembentukan ketebalan IMC dalam sambungan pateri komponen BGA di bawah pelbagai tetapan kerja semula dan TCT. Menggunakan data kajian yang meluas, model ANN menunjukkan prestasi ramalan yang baik dengan nilai koefisien penentuan, R-Kuasa 2 ($R^2$) 0.9603 untuk latihan dan 0.9846 untuk pengesahan. Graf sebenar berbanding terunjur mengesahkan kebolehharapan model, manakala pengimbasan mikroskop elektron (SEM) pada sampel keratan rentas mengesahkan ketepatan model, mendedahkan korelasi yang kuat dengan ketebalan IMC yang diramalkan pada kedua-dua sisi substrat BGA dan pad kuprum PCB. Pendekatan ini menunjukkan keberkesanan penggabungan kecerdasan buatan dan analisis eksperimen untuk pengoptimuman kaedah kerja semula, meningkatkan kebolehharapan sambungan pateri dan mengurangkan keperluan untuk ujian berintensif sumber dalam pembuatan elektronik berketumpatan tinggi.

# CHARACTERIZATION AND RELIABILITY OF BGA COMPONENT SAC305 SOLDER JOINTS USING TWO HEAT TRANSFER TYPES FOR REWORK PROCESS METHODS

## ABSTRACT

This thesis presents a comprehensive investigation into the characterization and reliability of ball grid array (BGA) SAC305 solder joints subjected to rework processes methods using distinct heat transfer mechanisms, convective heating in hot air rework and radiative heating in laser rework under accelerated thermal cycling conditions. SAC305 solder alloy was utilized on an organic solderability preservative (OSP) printed circuit board (PCB), and thermal cycling tests (TCT) were performed at 0 and 900 cycles to replicate operating conditions. A comparative analysis indicated that laser rework produced much lower thermal stress than hot air rework, resulting in less mechanical damage to adjacent solder joints. Post-TCT assessments utilizing dye and pull (DnP) tests revealed that laser reworked samples had 3.33% and 13.73% less damage than hot air reworked samples under pre and post cycle circumstances, respectively. To further understand the general failure mechanisms in BGA component solder joints, this study incorporates strain energy density (SED) analysis to identify areas most likely to crack. Simulation results show that the highest SED values, up to 3.4048 Pa, appeared at the edges of the solder joints array, while the lowest values, around 0.01803 Pa, were found near the center. This distribution helps locate the most stressed regions, where cracks are likely to start. The SED contour map allows comparison between simulated and actual failure locations, with the highest SED values indicating the likely site of the first solder ball failure. This method improves the understanding of failure behavior and supports more reliable design and rework strategies for high-density electronic assemblies. Furthermore, this thesis explores the effects of rework processes and thermal aging on intermetallic compound (IMC) formation at the BGA and PCB substrates' interfaces. Measurements on reworked (U123) and adjacent (U129) components demonstrated that hot air rework induced uniform but thermally widespread IMC development, whereas laser rework resulted in more localized and varied growth patterns, notably at the PCB interface. Based on these findings, this study presents a novel artificial neural network (ANN) approach for predicting IMC thickness growth in BGA solder joints under a variety of rework and TCT settings. Using substantial experimental data, the ANN model demonstrated good predictive performance, with R-Square ($R^2$) values of 0.9603 for training and 0.9846 for validation. Actual versus projected graphs verified the model's reliability, while scanning electron microscopy (SEM) of cross-sectional samples validated the model's accuracy, revealing a strong correlation with predicted IMC thickness on both the BGA and PCB sides. This approach demonstrates the effectiveness of merging artificial intelligence and experimental analysis to optimize rework parameters, improve solder joint reliability, and reduce the need for resource intensive testing in high density electronics manufacturing.

**KANDUNGAN**

## SENARAI JADUAL

## SENARAI ILUSTRASI

# SENARAI SINGKATAN

| | |
|---|---|
| Ag | Perak |
| AI | Kecerdasan Buatan |
| ANN | Rangkaian Neural Buatan |
| ANOVA | Analisis Varians |
| ASME | *The American Society of Mechanical Engineers* |
| BGA | Tatasusunan Grid Bebola |
| BSE | Elektron Berselerak Belakang |
| CFD | Pengiraan Bendalir Dinamik |
| CTE | Pekali Pengembangan Haba |
| Cu | Kuprum |
| DL | Pembelajaran Mendalam |
| DOE | Reka Bentuk Eksperimen |
| DnP | Ujian Pencelup dan Tarikan |
| EMS | Perkhidmatan Pembuatan Elektronik |
| EPFM | Mekanik Patah Elastoplastik |
| FEA | Analisis Elemen Terhingga |
| HR0 | Set Kajian Kerja Semula Udara Panas Sebelum TCT |
| HR900 | Set Kajian Kerja Semula Udara Panas Selepas TCT900 |
| I/O | Masukan dan Keluaran |
| IC | Litar Bersepadu |
| IMC | Sebatian Antara Logam |
| LCD | Paparan Hablur Cecair |
| LED | Diod Pancaran Cahaya |
| LEFM | Mekanik Patah Elastik Linear |
| LR0 | Set Kajian Kerja Semula Laser Sebelum TCT |

| | |
|---|---|
| LR900 | Set Kajian Kerja Semula Laser Selepas TCT900 |
| ML | Pembelajaran Mesin |
| Ni | Nikel |
| NLPRWK | Kerja Plastik Tidak Linear |
| OLED | Diod Pancaran Cahaya Organik |
| OPS | Penggilap Penggantungan Oksida |
| OSP | Pengawet Kebolehpematerian Organik |
| Pb | Plumbum |
| PBB | Pertubuhan Bangsa-Bangsa Bersatu |
| PCB | Papan Litar Bercetak |
| PCBA | Pemasangan Papan Litar Bercetak |
| PGA | Tatasusunan Grid Pin |
| PR0 | Set Kajian Tanpa Kerja Semula (Kawalan) Sebelum TCT |
| PR900 | Set Kajian Tanpa Kerja Semula (Kawalan) Selepas TCT900 |
| QFP | Pakej Quad Rata |
| $R^2$ | Nilai Koefisien Penentuan, R-Kuasa 2 |
| RSM | *Response Surface Methodology* |
| SAC305 | 96.5Sn-Ag3.0-Cu0.5 |
| SDG | Matlamat Pembangunan Lestari |
| SE | Elektron Sekunder |
| SED | Ketumpatan Tenaga Terikan |
| SEM | Mikroskop Elektron Pengimbasan |
| Sn | Timah |
| Sn-Ag-Cu, SAC | Timah-Perak-Kuprum |
| SVM | Mesin Vektor Sokongan |
| TC | Pengganding Suhu |

| | |
|---|---|
| TCT | Ujian Kitaran Haba |
| TCT0 | Tanpa/Sebelum TCT |
| TCT900 | 900 Kitaran TCT |
| UNITAR | *United Nations Institute for Training and Research* |

## SENARAI SIMBOL

| | |
|---|---|
| % | Peratusan |
| $\nabla$ | Kecerunan Suhu |
| $A$ | Luas Permukaan |
| $a_{j,m}$ | Keluaran Pengaktifan |
| $b$ | Pemalar Kadar Pertumbuhan IMC |
| $c_k$ | Bias |
| $c_p$ | Kapasiti Haba Tentu |
| $d$ | Ketebalan IMC |
| $E_{vol}$ | Isipadu Unsur |
| $G$ | Modulus Ricih |
| $h$ | Pekali Pemindahan Haba Olakan |
| $k$ | Kekonduksian Haba Bahan |
| $k_B$ | Pemalar Boltzmann |
| $L$ | Jarak Antara Sambungan Pateri BGA dan Titik Neutral Pakej Komponen BGA |
| $m$ | Neural |
| $N$ | Jumlah Neural Tersembunyi |
| $n$ | Ketinggian Sambungan Pateri Komponen BGA |
| $P$ | Jumlah Kuasa Laser |
| $q$ | Vektor Fluks Haba |
| $Q$ | Tenaga Pengaktifan |
| $r^2$ | Jarak Jejari dari Pusat Muncung Udara Panas atau Pusat Sinaran Laser |
| $\Sigma$ | Penjumlahan |
| $t$ | Masa |
| $T$ | Suhu |

| | |
|---|---|
| $v_{jk}$ | Pemberat yang Menghubungkan Neural Tersembunyi $z_j$ |
| $W$ | Kerja |
| $x$ | Vektor Masukan |
| $y_k$ | Ramalan Keluaran Akhir |
| $z_j$ | Keluaran Lapisan Neural Tersembunyi |
| $\alpha$ | Kemeresapan Haba Bahan, Parameter Penyebaran Haba |
| $\alpha_b$ | Pekali Pengembangan Haba PCB |
| $\alpha_p$ | Pekali Pengembangan Haba Pakej Komponen BGA |
| $\delta$ | Anjakan Ricih Relatif Nominal |
| $\Delta h$ | Penggunaan Ketebalan Substrat Kuprum |
| $\rho$ | Ketumpatan Bahan |
| $\sigma$ | Pemalar Stefan-Boltzmann |
| $\tau$ | Tegasan Ricih Nominal |
| $\varphi$ | Keamatan Aliran Udara |
| $\omega$ | Jejari Sinaran (Saiz Titik) Laser |

# BAB I

# PENGENALAN

## 1.1 PENDAHULUAN

Komponen tatasusunan grid bebola (*ball grid array* (BGA)) digunakan secara meluas dalam reka bentuk pemasangan papan litar bercetak (*printed circuit board assembly* (PCBA)) berketumpatan tinggi kerana keupayaannya untuk menyokong sejumlah besar sambungan masukan dan keluaran (*input*/*output* (I/O)) dalam ruang yang terhad (Ghenam et al. 2024). Walau bagaimanapun, proses kerja semula (*rework*) untuk komponen BGA dalam reka bentuk susunan komponen BGA yang padat di atas PCBA merupakan cabaran yang amat ketara, terutamanya apabila melibatkan kesan haba kaedah kerja semula pada komponen berdekatan (Kanso et al. 2017). Dalam tesis ini, istilah “kaedah” merujuk kepada teknik eksperimen kerja semula yang spesifik dan dipilih untuk memperoleh data, manakala “proses” menggambarkan rangkaian langkah berurutan yang menyepadukan kaedah tersebut bagi mencapai objektif penyelidikan secara menyeluruh. Memandangkan arah aliran saiz peranti elektronik moden terus mengecil dan mempunyai fungsi yang rumit, kebolehharapan proses kerja semula komponen BGA adalah penting untuk mengekalkan fungsi keseluruhan dan jangka hayat peranti elektronik (Saeed et al. 2024).

Kaedah kerja semula yang berkesan diperlukan untuk mengurangkan risiko kerosakan haba pada komponen berdekatan, yang boleh menyebabkan kegagalan atau penurunan (*degradation*) prestasi dari semasa ke semasa (Bődi & Gonda 2025). Secara umumnya, kaedah kerja semula udara panas telah menjadi kaedah utama untuk kerja semula komponen BGA, tetapi ia terdedah kepada pemanasan tidak sekata, yang mungkin memberi kesan kepada keutuhan komponen bersebelahan (Pandey et al. 2022). Kerja semula laser, dengan keupayaannya untuk menyasarkan kawasan yang tepat dengan sebaran haba yang minimum, menawarkan alternatif yang berpotensi mengurangkan risiko ini (Ji et al. 2023). Walau bagaimanapun, kebolehharapan kedua-dua kaedah ini perlu dinilai secara kuantitatif dan kualitatif untuk memastikan ia tidak menjejaskan ketahanan PCBA selepas proses kerja semula.

Walaupun terdapat penyelidikan yang meluas dalam keboleharapan pemasangan elektronik dan kaedah kerja semula, terdapat beberapa jurang kritikal yang masih wujud berkenaan dengan impak spesifik mekanisme pemindahan haba yang berbeza terhadap keboleharapan sambungan pateri 96.5Sn-Ag3.0-Cu0.5 (SAC305) dalam komponen BGA yang dikerja semula dan bersebelahan. Kajian terdahulu telah menilai secara meluas kebolehharapan sambungan pateri di bawah kaedah kerja semula udara panas, namun analisis perbandingan yang terperinci melibatkan kerja semula udara panas dan laser, terutamanya yang menekankan peranan perbezaan antara mekanisme pemindahan haba olakan dan sinaran, masih agak terhad terutamanya yang melibatkan komponen BGA bersebelahan dengan komponen yang dikerja semula.

Huang et al. (2020) menyatakan dalam secara umum dalam perbincangan mereka tentang prestasi komponen BGA yang dikerja semula dipengaruhi oleh faktor seperti suhu kerja semula yang tinggi dengan hanya merujuk kepada mekanisme pemindahan haba olakan, sekaligus mengurangkan ketinggian sambungan pateri, peningkatan ketebalan sebatian antara logam (*intermetallic compound* (IMC)) antara muka yang mengurangkan kemuluran dan pembentukan fasa mikrostruktur yang kaya plumbum (Pb) dan lebih homogen dalam pemasangan pateri bercampur dapat meningkatkan ketahanan kelesuan dengan melambatkan penghabluran semula dan kekasaran butiran. Penyelidikan Wiss et al. (2024) adalah tentang kesan haba pematerian pada komponen elektronik, menggunakan kaedah pengaliran semula dan kerja semula, dengan kitaran pengaliran semula tambahan berserta kerja semula udara panas, manakala sampel disiasat melalui mikroskop optik, manakala model simulasi pengiraan bendalir dinamik (*computational fluid dynamics* (CFD)) telah dibangunkan untuk menilai impak termomekanikal dengan mensimulasikan mendedahan udara panas ke atas komponen. Kim et al. (2023) membentangkan kajian tentang pematerian laser berkelajuan tinggi dan teknologi kerja semula laser automatik sepenuhnya untuk komponen diod pancaran cahaya (*light emitting diod* (LED)) mini dalam paparan

paparan hablur cecair (*liquid crystal display* (LCD)), menangani cabaran utama dalam prestasi pengikatan dan daya pemprosesan pada papan litar bercetak (PCB) fleksibel nipis untuk memanjangkan daya saing LCD terhadap diod pancaran cahaya organik (*organic light emitting diod* (OLED)) dengan membolehkan pemasangan dan kerja semula LED mini yang tepat dan berprestasi tinggi.

Di samping itu, kesusasteraan sedia ada kebanyakannya menumpukan pada hasil keboleharapan umum tanpa meneroka secara menyeluruh hubungan asas antara fenomena pemindahan haba setempat, evolusi mikrostruktur, pertumbuhan IMC, dan kesan seterusnya terhadap keutuhan sambungan pateri dan hayat lesu. Wooi (2024) telah melakukan perbandingan kerja semula udara panas terhadap komponen BGA dengan dan tanpa menggunakan pelindung haba. Selain dari perbezaan haba komponen BGA yang di kerja semula, parameter lain yang diperhatikan adalah kadar pemindahan haba dari sumber udara panas ke komponen BGA, masa kitar proses kerja semula dan kos kerja semula adalah lebih baik apabila kerja semula menggunakan pelindung haba. Penyelidikan Chang et al. (2024) dalam evolusi mikrostruktur yang berlaku pada komponen BGA yang dikerja semula dan bersebelahan ditemui dengan menganalisis evolusi mikrostruktur IMC dalam komponen ini semasa pematerian kerja semula udara panas, menggunakan mikroskop elektron pengimbasan (*scanning electron microscopy* (SEM)). Penemuan ini mendedahkan bahawa kaedah kerja semula menyebabkan kekasaran butiran dalam komponen kerja semula dan komponen bersebelahan. Kekurangan analisis perbandingan yang terperinci dan khusus mekanisme ini mewakili jurang yang ketara, mengehadkan pengoptimuman kaedah kerja semula yang disesuaikan dengan pakej komponen BGA berketumpatan tinggi yang biasa ditemui dalam peranti elektronik terkini.

Teknik kerja semula berasaskan laser, memanfaatkan aplikasi haba yang tepat dan setempat terutamanya melalui sinaran yang ditambah dengan olakan, boleh mengurangkan pendedahan haba yang tidak diingini bagi komponen bersebelahan, sekali gus meningkatkan keboleharapan sambungan pateri (Abdalla et al. 2023). Pemindahan haba olakan, dikawal secara asas oleh Hukum Penyejukan Newton, membenarkan pelesapan terkawal dan profil pemanasan seragam (Jiang et al. 2021), manakala pemindahan haba sinaran, yang diterangkan oleh Hukum Stefan-Boltzmann, memudahkan pemindahan tenaga yang disasarkan dengan kesan pemanasan cagaran yang minimum (Odebowale et al. 2025). Dengan meneliti mekanisme ini dengan teliti, kajian ini berusaha untuk menjelaskan hubungan asas antara kawalan haba yang tepat, kestabilan mikrostruktur IMC dan keutuhan mekanikal yang dipertingkatkan, akhirnya menyediakan asas saintifik yang penting untuk pengoptimuman kaedah kerja semula dalam komponen BGA.

## 1.2 PERMASALAHAN DAN MOTIVASI KAJIAN

Dalam reka bentuk pemasangan PCBA berketumpatan tinggi, kaedah kerja semula komponen BGA yang tidak dilaksanakan dengan betul boleh menyebabkan peningkatan tegasan haba pada kawasan setempat (Otahal et al. 2017). Tegasan haba ini bukan sahaja memberi kesan kepada komponen sasaran yang dikerja semula, malah turut menjejaskan komponen yang bersebelahan, yang akhirnya boleh menyebabkan penurunan pada sambungan pateri bebas Pb yang berasaskan bahan timah-perak-kuprum (Sn-Ag-Cu, SAC) dan mengurangkan prestasi jangka panjang sistem elektronik (Tang et al. 2012). Kesan ini menjadi lebih ketara apabila peranti elektronik terdedah kepada keadaan persekitaran yang berubah-ubah seperti ujian kitaran haba, yang boleh mempercepatkan kegagalan mekanikal dan fungsi elektrik sambungan pateri komponen BGA (Peng et al. 2025).

Kaedah kerja semula konvensional, seperti penggunaan udara panas, sering kali gagal dalam mengawal profil haba secara tepat, menjadikan sambungan pateri komponen sekeliling lebih terdedah kepada tegasan haba yang berlebihan (Wiese et al. 2025). Kekangan ini menimbulkan cabaran besar dalam mengekalkan kebolehharapan sambungan pateri, terutamanya apabila komponen berada dalam jarak rapat pada reka bentuk yang padat (Blackman 2015). Dalam persekitaran industri seperti aeroangkasa, automotif dan telekomunikasi yang menuntut tahap kebolehharapan tinggi, kerosakan pada sambungan pateri boleh membawa kepada kegagalan sistem kritikal, justeru memerlukan penilaian semula terhadap teknik kerja semula sedia ada dan pengenalpastian kaedah alternatif yang lebih selamat (Noh et al. 2024; Qi 2023; Tian et al. 2024; Henttonen et al. 2018).

Motivasi penyelidikan ini turut didorong oleh dinamik rantaian bekalan global dan keperluan kecekapan kos dalam industri perkhidmatan pembuatan elektronik (*electronic manufacturing services* (EMS)) (Rogers et al. 2024). Apabila berlaku kekurangan bekalan komponen elektronik, kaedah kerja semula memainkan peranan penting dengan membolehkan produk yang mengalami kecacatan semasa pembuatan dibaiki semula, sekali gus mengurangkan kebergantungan kepada komponen gantian baharu dan meminimumkan impak gangguan rantaian bekalan (Lalremruati & Khanna 2025). Selain itu, pelaksanaan kerja semula yang cekap mampu mengurangkan kadar sekerap (*scrap*) yang melibatkan kos sangat tinggi dalam reka bentuk PCBA berketumpatan tinggi, seterusnya meningkatkan margin keuntungan serta kelestarian operasi syarikat (Dias et al. 2018; Zwane & Schoeman 2025; Goyal et al. 2023).

Dari perspektif alam sekitar, kajian ini merupakan langkah penting dalam pengurusan pencegahan sisa elektronik (*e-waste* (e-sisa)) yang kini memberi implikasi serius terhadap kesihatan manusia (Akour & Alenezi 2025). Pelaksanaan kaedah kerja semula yang berkesan dapat mengurangkan keperluan untuk melupuskan keseluruhan pemasangan papan litar, sekali gus mengurangkan jumlah e-sisa yang dijana akibat kegagalan komponen. Penyelidikan ini menyokong penuh inisiatif pemanjangan kitaran hayat produk melalui pendekatan kerja semula yang mampan, sejajar dengan usaha global ke arah amalan pengeluaran yang lebih lestari dan mesra alam (Singh et al. 2025).

Akhir sekali, kajian ini menyahut seruan 17 Matlamat Pembangunan Lestari (*Sustainable Development Goals* (SDG)) yang digariskan oleh Pertubuhan Bangsa-Bangsa Bersatu (PBB), terutamanya Matlamat 9 mengenai industri dan inovasi, Matlamat 12 berkaitan penggunaan bertanggungjawab, serta Matlamat 13 mengenai tindakan iklim (Anuardo et al. 2023; Raman et al. 2025; Nauman et al. 2025). Dengan meneliti kaedah kerja semula berteknologi tinggi seperti penggunaan laser yang memanfaatkan pemindahan haba sinaran, kajian ini bertujuan membandingkan keberkesanannya terhadap kaedah udara panas untuk meminimumkan sebaran haba (Bakhoum 2019). Pendekatan ini bukan sahaja memupuk inovasi teknologi yang menyumbang kepada pengurangan impak alam sekitar, malah menyediakan asas teknikal yang kukuh untuk penghasilan garis panduan kerja semula yang lebih berkesan dalam industri elektronik.

## 1.3 PERSOALAN KAJIAN

Kajian ini bermatlamat untuk menjawab beberapa persoalan asas berkaitan kesan termomekanikal terhadap integriti komponen elektronik melalui perbandingan antara kaedah kerja semula laser dan udara panas. Soalan utama yang dikaji adalah sejauh manakah perbezaan profil pendedahan haba antara mekanisme pemindahan haba sinaran (laser) dan olakan (udara panas) memberi kesan terhadap komponen BGA sasaran serta komponen bersebelahan dalam reka bentuk PCBA berketumpatan tinggi. Selain itu, kajian ini mempersoalkan bagaimana perubahan mikrostruktur, terutamanya evolusi pertumbuhan ketebalan lapisan IMC, mempengaruhi prestasi kebolehharapan dan hayat kelesuan sambungan pateri apabila didedahkan kepada tekanan persekitaran melalui ujian kitaran haba (*thermal cycle test* (TCT)).

Seterusnya, penyelidikan ini meneroka keberkesanan integrasi teknologi kecerdasan buatan (*artificial intelligence* (AI)) dalam meramal kegagalan sambungan pateri bagi aplikasi industri berprestasi tinggi. Persoalan kritikal yang ditimbulkan adalah sejauh manakah model rangkaian neural buatan (*artificial neural network* (ANN)) berupaya mengenal pasti pola data yang kompleks daripada parameter kerja semula dan hasil analisis fizikal seperti ujian pencelup dan tarikan (*dye and pull* (DnP)), pemeriksaan optikal keratan rentas dan analisis SEM untuk menghasilkan ramalan kebolehharapan yang tepat. Akhir sekali, kajian ini menyiasat bagaimana pengoptimuman parameter proses kerja semula ini dapat memberikan impak signifikan terhadap pengurangan sisa elektronik e-sisa serta kemampanan ekonomi dalam kitaran hayat produk elektronik.

## 1.4 HIPOTESIS KAJIAN

Hipotesis kajian ini menyatakan bahawa kaedah kerja semula berasaskan laser mampu menghasilkan tegasan haba yang lebih rendah ke atas komponen sekeliling berbanding kaedah kerja semula menggunakan udara panas. Pengurangan tegasan haba ini dijangka dapat mengurangkan kerosakan haba tidak langsung pada sambungan pateri, sekali gus meningkatkan kebolehharapan sambungan, serta prestasi jangka panjang keseluruhan pemasangan PCBA, khususnya dalam reka bentuk berketumpatan tinggi.

Selain itu, adalah dihipotesiskan bahawa penggunaan model rangkaian neural buatan ANN dapat memberikan ramalan yang tepat terhadap kebolehharapan sambungan pateri berdasarkan pelbagai parameter kaedah dan persekitaran seperti jenis kerja semula, suhu maksimum, bilangan kitaran haba dan ketebalan IMC. Dengan keupayaan pembelajaran tidak linear, ANN dijangka mampu mengenal pasti pola tersembunyi dalam data eksperimen dan menyediakan satu kaedah ramalan yang boleh dipercayai untuk menyokong pengoptimuman kaedah kerja semula bagi komponen BGA dalam aplikasi elektronik berprestasi tinggi.

## 1.5 OBJEKTIF KAJIAN

Objektif utama kajian ini adalah untuk menilai keberkesanan kaedah kerja semula komponen BGA dengan menggunakan dua kaedah pemindahan haba yang berbeza, iaitu udara panas dan laser, dalam usaha mengurangkan kesan haba terhadap komponen sekeliling pada reka bentuk PCBA berketumpatan tinggi. Penilaian ini bertujuan untuk mengenal pasti kaedah kerja semula yang lebih selamat dan efisien bagi memastikan keutuhan sambungan pateri tidak terjejas akibat penyebaran haba semasa kaedah kerja semula.

Sebagai sebahagian daripada objektif kajian, kebolehharapan sambungan pateri pada pemasangan yang telah dikerja semula akan dianalisis secara menyeluruh melalui pelaksanaan ujian kitaran haba, serta pelbagai teknik analisis fizikal seperti pemeriksaan optikal, analisis keratan rentas dan pemerhatian mikrostruktur menggunakan SEM. Selain itu, kajian ini turut bertujuan membangunkan model ramalan berasaskan ANN untuk meramalkan kebolehharapan sambungan pateri selepas kerja semula. Pemodelan ini diharap dapat membantu dalam memahami saling tindak pelbagai parameter kaedah kerja semula dan menyediakan asas kepada pengoptimuman strategi kerja semula yang lebih tepat dan berdaya saing untuk aplikasi elektronik industri berprestasi tinggi.

Pemilihan ANN berbanding kaedah *response surface methodology* (RSM) atau kaedah Taguchi tradisional adalah berlandaskan keperluan untuk memperihalkan hubungan tidak linear yang sangat kompleks antara parameter kerja semula dan tindak balas mikrostruktur IMC yang tidak dapat dipetakan secara tepat oleh model polinomial darjah rendah dalam RSM. Walaupun RSM merupakan amalan standard dalam industri untuk pengoptimuman proses linear, pendekatan ANN dalam tesis ini adalah lebih progresif dan sejajar dengan Revolusi Industri 4.0, yang mana keupayaan pembelajaran mesin (*machine learning* (ML)) digunakan untuk mengurus varians data yang tinggi. Penggunaan fungsi pengaktifan tanH dan Gaussian dalam model ANN membolehkan simulasi interaksi antara pemboleh ubah (kaedah kerja semula, kitaran TCT, dan jenis komponen) dilakukan dengan lebih dinamik berbanding model permukaan statik dalam reka bentuk eksperimen (*design of experiments* (DOE)) konvensional. Oleh itu, kerangka kerja sedia ada dalam tesis ini bukan sahaja berfungsi sebagai alat ramalan, malah membuktikan bahawa peralihan kepada ANN adalah perlu bagi mencapai tahap pengoptimuman kebolehharapan sambungan pateri yang lebih jitu dalam persekitaran kejuruteraan proses moden.

## 1.6 OBJEKTIF KHUSUS

Untuk mencapai objektif kajian, objektif khusus berikut ditakrifkan:

1. Untuk membandingkan kesan pendedahan haba antara kaedah kerja semula laser dan udara panas terhadap komponen BGA sasaran serta komponen BGA bersebelahan pada papan litar bercetak berkepadatan tinggi.

2. Untuk menilai kebolehharapan sambungan pateri hasil kerja semula melalui pendedahan set kajian kepada ujian TCT.

3. Untuk mencirikan kesan kaedah kerja semula dan penuaan haba terhadap antara muka sambungan pateri BGA dan PCB melalui analisis fizikal merangkumi ujian DnP, keratan rentas, pemeriksaan optikal, SEM, serta pengukuran ketebalan lapisan IMC.

4. Untuk membangunkan dan mengesahkan model ANN bagi meramalkan kebolehharapan sambungan pateri berdasarkan parameter kaedah kerja semula dan dapatan analisis fizikal.

## 1.7 SKOP KAJIAN DAN TESIS

Penyelidikan ini memberi tumpuan khusus kepada penilaian dua kaedah kerja semula utama iaitu laser dan udara panas yang digunakan dalam proses kerja semula komponen BGA pada reka bentuk PCBA berketumpatan tinggi. Skop kajian merangkumi pelaksanaan ujian eksperimen seperti ujian kitaran haba untuk menilai kebolehharapan sambungan pateri berasaskan aloi pateri SAC305, serta analisis fizikal secara terperinci terhadap mikrostruktur sambungan pateri dan komponen BGA bersebelahan selepas proses kerja semula menggunakan kaedah seperti pemeriksaan optikal, keratan rentas, dan analisis SEM. Selain itu, penyelidikan ini turut menerapkan pendekatan ML melalui ANN bagi meramalkan tahap kebolehharapan sambungan pateri berdasarkan pelbagai parameter rekaan dan proses yang bertujuan menyokong pengoptimuman kaedah kerja semula dalam pemasangan PCBA berketumpatan tinggi.

Kajian dalam tesis ini dibahagikan kepada dua bahagian utama, iaitu bahagian eksperimen dan bahagian pemodelan, yang dirangka secara menyeluruh untuk memahami dan meningkatkan kebolehharapan sambungan pateri komponen BGA dalam konteks kaedah kerja semula. Kajian ini dilaksanakan dalam tiga fasa yang saling melengkapi, dengan tujuan utama untuk menilai kesan sumber haba dan parameter persekitaran terhadap prestasi mekanikal dan struktur sambungan pateri, khususnya dalam reka bentuk PCBA berketumpatan tinggi. Pemahaman yang lebih mendalam terhadap saling tindak antara sumber haba dan bahan sambungan pateri dijangka dapat menyumbang kepada peningkatan mutu dan kebolehharapan produk elektronik.

Fasa pertama kajian menilai kesan haba daripada kaedah kerja semula terhadap sambungan pateri komponen BGA yang bersebelahan dengan komponen yang telah dikerja semula, bagi mengenal pasti risiko kerosakan tidak langsung akibat penyebaran haba. Fasa kedua memfokuskan kepada pemerhatian pertumbuhan lapisan IMC hasil daripada pendedahan kepada pelbagai jenis sumber haba semasa kerja semula. Dalam fasa ketiga, pendekatan pemodelan diterapkan melalui penggunaan ANN untuk meramalkan ketebalan IMC berdasarkan data eksperimen, jenis kaedah kerja semula dan parameter ujian kitaran haba. Pendekatan hibrid ini menggabungkan penemuan eksperimen dengan AI untuk menyediakan ramalan prestasi yang tepat dan menyokong

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