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A Systematic Literature Review on the Application of Artificial Neural Networks for Predicting Sn-Cu Lead-Free Solder Joint Strength

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ABSTRACT

Artificial neural networks (ANNs) are increasingly used to predict the mechanical strength and reliability of Sn-Cu lead-free solder joints in modern electronic packaging. However, current research shows varying modelling practices and limited comparison across methods. This paper reviews ANN applications in predicting Sn-Cu solder joint strength using a structured search on Scopus and Web of Science, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyse (PRISMA) guidelines. A total of 21 relevant studies were analysed. The review identifies three key research directions: (i) ANN-based prediction of solder joint strength and reliability with improved accuracy over empirical and finite-element models; (ii) fatigue, creep and life prediction models for lead-free solders under diverse thermomechanical loading; and (iii) hybrid AI techniques such as genetic algorithms and physics-guided networks that enhance performance and model robustness. The review reveals that ANN models consistently outperform traditional predictive techniques; however, challenges persist in data scarcity, experimental complexity and the integration of micro-mechanistic knowledge into learning architectures. This evidence underscores the necessity for hybrid physics-guided ANN models and standardised benchmarking protocols to advance reliable prediction ecosystems for Sn–Cu solder interconnects in mission-critical applications.

Keywords: Artificial Neural Networks (ANN), Lead-Free Solder Joints, Sn–Cu Alloys, Reliability Prediction

1. INTRODUCTION

The transition from traditional lead-based solders to environmentally safer alternatives such as Sn-Cu alloys has become a key priority in modern electronics manufacturing. In this context, Artificial Neural Networks (ANNs) have gained prominence as effective computational tools capable of modelling the nonlinear interactions between alloy composition, processing parameters and joint performance. ANNs can accurately predict properties such as tensile and shear strength, reducing dependence on extensive physical testing and enabling faster optimization of solder materials and processes [1][2]. Early studies confirmed the capability of multilayer perceptions trained via backpropagation to capture complex relationships between microstructural evolution (e.g., intermetallic compound formation) and mechanical behaviour [3]. Hybrid modelling approaches that integrate empirical data with physics-based simulations are also gaining traction due to their enhanced robustness and interpretability, especially when validated using experimental tensile and hardness data [4][5][6]. Variations in thermal cycling

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profiles, measurement uncertainties and manufacturing inconsistencies can affect model performance, raising questions about the transferability of ANN models developed in controlled laboratory settings to industrial applications [7]. Future research should therefore prioritize the incorporation of stochastic training strategies, hybrid ANN-physics models, and improved feature selection methods to enhance model robustness and prediction accuracy [8][9].

2. LITERATURE REVIEW

2.1 Introduction to ANN in Solder Joint Strength Prediction

ANNs have been increasingly applied to predict the mechanical behaviours and reliability of lead-free solder joints, particularly in Sn-Cu systems. Their primary advantage lies in modelling complex nonlinear relationships between input variables (e.g., alloy composition, aging conditions) and outputs such as tensile and shear strength. For example, Backpropagation (BP) neural networks have accurately predicted the mechanical properties of Sn-Ag alloys with various additives [10]. Similarly, ANNs have been successfully used to predict yield strength, tensile strength, and elongation in Cu-Sn-Pb-Zn-Ni cast alloys [11].

2.2 Comparative Analysis and Future Directions

As summarized in Table 1, ANN models have consistently demonstrated high predictive accuracy for solder joint strength. For example, the ANN model used for Sn-5Sb solder joints reinforced with multi-walled carbon nanotubes (MWCNTs) effectively predicted both IMC thickness and shear strength, outperforming conventional models [13][14]. The integration of machine learning with finite element simulation has also shown strong potential, particularly in predicting fatigue life under dynamic conditions such as harmonic vibration [15].

Table 1 ANN models for solder joint strength prediction

Focus	Alloy	Model	Inputs	Outputs	Findings
Tensile and Shear Prediction	Sn-Ag + additives	BP Neural Net	In, Bi, Sb, RE, Sn, Ag, Cu	Tensile, shear strength, solid temperature	High accuracy [10]
Mechanical Properties	Cu-Sn-Pb-Zn-Ni	MLP + BP	Cu, Sn, Pb, Zn, Ni	Yield, tensile strength, elongation	Successful predictions [11]
Hardness Prediction	Sn-9Zn-Cu	ANN	Cu content, aging time	Vickers hardness	MSE = 9.55E–06 [1]
Stress–Strain Curve	SAC305	ANN	Aging time, temp, strain rate	Stress–strain curves	R^2 = 0.9995 [12]
IMC and Shear Strength	Sn-5Sb + MWCNTs	AO–ELM	MWCNTs %, aging temp, time	IMC thickness, shear strength	Outperformed traditional models [13][14]

In conclusion, the application of ANNs in predicting the mechanical properties of Sn-Cu lead-free solder joints has shown significant promise. These models can accurately predict various properties, aiding in the design and optimization of reliable solder joints for electronic packaging. Future research should focus on refining these models and exploring their integration with other machine learning techniques to further enhance prediction accuracy and applicability.

3. MATERIAL AND METHODS

3.1 Identification

The identification stage followed the PRISMA guidelines and began with the development of relevant keywords related to Artificial Neural Networks (ANNs), lead-free solder joints, and Sn-Cu systems. Keywords were refined using dictionaries, thesauri, encyclopaedia and previous studies to ensure terminological completeness. Search strings were then formulated for the Scopus and Web of Science (WoS) databases, as shown in Table 2.

Table 2 The search string

Scopus	TITLE-ABS-KEY (TITLE-ABS-KEY (artificial neural network) AND TITLE-ABS-KEY (soldered joints)) AND PUBYEAR > 2021 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE,"ar"))) Date of Access: Oct 2025
WoS	(Artificial Neural Network AND Lead -Free Solder Joint) (Topic) and 2025 or 2021 (Publication Years) and Article (Document Types) and English (Languages) and Engineering (Research Areas) and Article (Document Types) and Engineering (Research Areas) Date of Access: Oct 2025

3.2 Screening

During this phase, duplicate papers were removed, resulting in 151 publications for further assessment based on predefined inclusion and exclusion criteria. Only English-language journal articles published between 2021 and 2025 within the engineering domain were included. Publications such as conference papers, reviews, books, and non-English items were excluded, as summarized in Table 3.

Table 3 The selection criterion

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2021 – 2025	< 2021
Literature type	Journal (article)	Conference, book, review
Subject	Engineering	Besides engineering

3.3 Eligibility

In the eligibility phase, 151 papers were assessed in detail through title and abstract screening. A total of 134 articles progressed to full-text evaluation. Studies were excluded if they were outside the research scope, lacked relevance to the objectives, offered insufficient methodological detail, or lacked full-text access. Consequently, 21 articles met all inclusion criteria and were selected for the final review.

3.4 Data Abstraction and Analysis

The process began with comprehensive abstract-level screening and data extraction, followed by iterative coding to categorise emerging themes and sub-themes linked to ANN applications in solder joint reliability modelling. As illustrated in Figure 1, a total of 21 scholarly sources were examined, with each publication reviewed for conceptual contributions, methodological suitability, and alignment with the overarching research focus. During synthesis, methodological frameworks and reported outcomes were critically compared, ensuring that both empirical and computational perspectives were incorporated into the thematic interpretation.

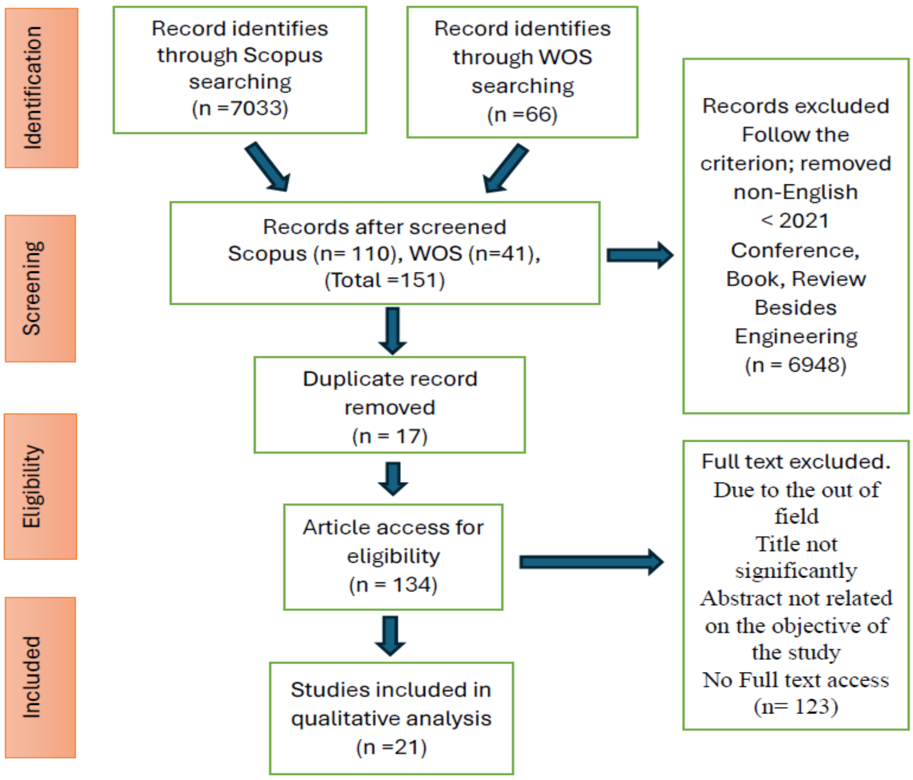

Figure 1. Flow diagram of the proposed searching study

Creep-driven strain evolution in multicomponent capacitor assemblies achieved prediction accuracy near 96%, with stand-off height and geometry identified as dominant factors influencing performance [16], while fracture behaviour models using ANN and random forest reached accuracies of 86% and 80.5%, further improved through multi-objective evolutionary optimisation [17].

Comparative analyses reported error rates below 3% across diverse thermal-cycling and ageing conditions, confirming ANN's superior generalisation and lower computational burden relative to traditional approaches [18]. ANN-based hybrid models also proved robust under data limitations, as physics-informed architectures incorporating autoregressive fatigue laws maintained stable predictions for aerospace-grade components subjected to shock-induced fatigue [19]. Memory-augmented recurrent networks supported fatigue detection in LED assemblies, though conventional ANN coupled with genetic-algorithm optimisation often delivered comparable accuracy with reduced complexity [20][21]. Furthermore, ANN integration with constitutive material models enhanced fatigue-life estimation under variable strain-rate regimes [22] and ANN-assisted creep predictions for Sn-based alloys closely matched experimental results while enabling extrapolation of rupture parameters otherwise impractical to measure [23]. Thermomechanical cycling studies additionally confirmed ANN's capability in identifying creep-to-fatigue transition behaviour, emphasising solder thickness and dwell temperature as critical determinants of failure evolution [24]. Collectively, the PRISMA-filtered evidence reinforces ANN's central role in accelerating reliability prediction, improving modelling fidelity, and supporting advanced electronic packaging under demanding operational conditions. Background of the selected study is presented in Table 4.

Table 4 Research articles findings based on the proposed searching criterion

No.	Author	Journal	Title	Scopus	WoS	Remarks
1	Alavi et al. (2025)	IEEE Transactions on Components, Packaging and Manufacturing Technology	Benchmarking Machine Learning Methods Against Finite Element and Empirical Models for Predicting Solder Joint Characteristic Life	/		Strong comparison across modelling approaches
2	Soroush et al. (2025)	Theoretical and Applied Fracture Mechanics	A Machine learning model to predict fracture of solder joints considering geometrical and environmental factors	/	/	Considers multifactor incl. environmental load
3	Su et al. (2025)	Journal of Mechanics	Study on the relationship between material curves, empirical models, critical mesh size and solder joint reliability life	/	/	Highlights mesh sensitivity & ML integration
4	Yu et al. (2025)	Microelectronics Reliability	Application of machine learning modeling for predicting the reliability of solder joints under thermal cycling	/	/	Strong thermal cycling correlation
5	Yuan et al. (2021)	Materials	Solder Joint Reliability Risk Estimation by AI-Assisted Simulation Framework with Genetic Algorithm to Optimize the Initial Parameters for AI Models	/	/	AI-assisted reliability workflow
6	Lebda et al. (2024)	Journal of Electronic Materials	Simulation and Prediction of Creep Rate, Activation Energy, and Rupture Time of Sn94Sb5Ag1 Lead-Free Solder Alloy Using Artificial Neural Network Modelling	/	/	Strong creep prediction capability
7	Ma et al. (2025)	International Journal of Fatigue	A data assisted physics-Informed neural network for predicting fatigue life of electronic components under complex shock	/	/	Good for sparse datasets
8	Zippelius et al. (2022)	Microelectronics Reliability	Reliability analysis and condition monitoring of SAC+ solder joints under high thermomechanical stress conditions using neuronal networks	/	/	Real-condition monitoring included
9	Chen et al. (2022)	Mechanics of Advanced Materials and Structures	Creep-fatigue lifetime estimation of SnAgCu solder joints using an artificial neural network approach	/	/	Effective for SAC solder
10	Ismail et al. (2025)	Springer proceedings	Artificial neural network Analysis for Predicting Gold Diffusions in solder joints under various rework	/		Limited scope; not Sn-Cu but ML-based
11	Abd El-Rehim et al. (2021)	Metals and Materials International	Mathematical Modelling of Vickers Hardness of Sn-9Zn-Cu Solder Alloys Using an Artificial Neural	/	/	Focus on hardness modelling

No.	Author	Journal	Title	Scopus	WoS	Remarks
12	Kumar et al. (2022)	IEEE Transactions on Electromagnetic Compatibility	Knowledge-Based Neural Networks for Fast Design Space Exploration of Hybrid Copper-Graphene On-Chip Interconnect Networks	/	/	Not solder-specific but valid ML
13	Reddad et al. (2024)	10th International Conference on Control, Decision and Information Technologies	Combining FEM and Machine Learning Algorithms for Reliability Prediction of Solder Ball Joints in BGA Packages	/		FEM + ML combined
14	Cao et al. (2024)	International Conference on Flexible Automation and Intelligent Manufacturing	A Hybrid Model for Solder Joint Height Prediction Based on Physical Knowledge and Machine Learning	/		Integrates domain knowledge
15	Zahran et al. (2021)	Crystals	Modelling the Effect of Cu Content on the Microstructure and Vickers Microhardness of Sn-9Zn Binary Eutectic Alloy Using an Artificial Neural Network	/	/	Useful for metallurgical optimization
16	Ismail et al. (2025)	IEEE 75th Electronic Components and Technology Conference	Predictive Modeling of IMC Growth in BGA Component Solder Joints Using Artificial Neural Networks Under Rework and Temperature Cycling Conditions	/		Strong relevance to solder reliability
17	Wei et al. (2025)	NPJ Computational Materials	Discovering novel lead-free solder alloy by multi-objective Bayesian active learning with experimental uncertainty	/	/	Alloy discovery focus
18	Ljubinković et al. (2025)	Structural Engineering International	Towards Stochastic Characterization of Welded Beam-to-Column steel joints using Artificial Neural Networks	/	/	Not solder-structural steel, but ML
19	Rebal et al. (2024)	Journal of Electronic Materials	Advanced Reliability Prediction of FBGA Solder Joints Under Harmonic Vibration: Harnessing Supervised Machine Learning Models	/	/	Harnessing supervised machine learning
20	Dele-Afolabi et al. (2021)	Journal Materials Characterization	Interfacial IMC evolution and shear strength of MWCNTs-reinforced Sn–5Sb composite solder joints: Experimental characterization and artificial neural network modelling	/		Composite solder reinforcement
21	Dele-Afolabi et al. (2024)	*Journal of Alloys and Compounds*	Performance assessment of Sn-based lead-free solder composite joints based on extreme learning machine model	/		Non-ANN model but ML-based

4. THEMES

4.1 Theme 1: ANN-Driven Prediction and Reliability Life Assessment of Solder Joint

This theme consolidates research employing machine learning and ANN to anticipate reliability degradation, thermal–mechanical failure mechanisms, and fracture behaviour. Works in this category benchmark predictive accuracy against physics-based simulations and empirical methods, underscoring ANN's growing predictive authority in electronics reliability engineering.

4.2 Theme 2: ANN-Based Fatigue, Creep and Life Prediction Models for Lead-Free Solder Alloys

Articles in this cluster emphasize time-dependent deformation models, particularly fatigue and creep behaviour. Using ANN to quantify lifetime evolution under complex loading regimes advances predictive capability for Sn-based solder alloys, bridging metallurgical degradation science with computational prognostics.

4.3 Theme 3: AI-Assisted Optimization and Hybrid Predictive Simulation Frameworks

This emerging niche integrates ANN with optimization algorithms and hybrid physics-simulation frameworks. It signifies a transition from predictive modelling alone toward multi-objective, computationally intelligent reliability optimisation, aligning with next-generation electronic packaging challenges.

4.4 Cross-Theme Synthesis

Across the three themes, ANN applications vary in scope, highlighting the field's progression from material-level prediction to system-level optimisation. Fatigue and creep studies use ANN to capture time-dependent degradation patterns, while IMC and reliability assessments employ ANN as a surrogate to model microstructural evolution and failure mechanisms. Hybrid optimisation frameworks further expand ANN's role by integrating it with physics-based models for multi-objective decision-making in advanced packaging. Collectively, these approaches demonstrate a shift toward more intelligent and adaptive reliability strategies, AI techniques, and materials engineering to enhance predictive accuracy and real-world applicability.

5. RESULTS AND DISCUSSION

5.1 Overview of ANN Performance in Predicting Solder Joint Strength

The analysis of 21 studies using the PRISMA method reveals that Artificial Neural Networks (ANNs) are highly effective in predicting the strength and reliability of Sn-Cu lead-free solder joints.

5.2 Modelling Fatigue, Creep and Life Prediction

The ANN model developed for Sn-9Zn-Cu solder alloys demonstrated high accuracy in predicting Vickers hardness, with mean square error values of 9.55E-06 and 9.44E-06 for training and validation data, respectively. Similarly, another study highlighted the ANN's capability to predict the lifetime of Sn-Ag-Cu-based solder joints under thermomechanical cycling, accurately distinguishing the roles of creep and fatigue in damage evolution [24].

5.3 Hybrid AI-Based Frameworks for Enhanced Optimization

The use of an Extreme Learning Machine (ELM) refined by the Aquila optimizer (AO) demonstrated superior performance in predicting the intermetallic compound (IMC) thickness and shear strength of MWCNTs-reinforced Sn5Sb/Cu composite solder joints. This hybrid approach outperformed traditional ANN models, showcasing the potential of combining different AI techniques for improved predictive capabilities.

5.4 Comparative Analysis with Empirical and FEM Methods

The ANN model for predicting the stress-strain curves of SAC305 solder alloys achieved a coefficient of determination, R^2 of 0.9995, indicating near-perfect accuracy. In contrast, traditional methods often struggle with the complexity and variability of solder joint properties, leading to less reliable predictions.

5.5 Practical Implications and Industrial Applications

The ability to accurately predict solder joint strength and reliability can lead to better design and manufacturing processes, reducing the likelihood of joint failures and extending the lifespan of electronic devices. The use of ANNs in predicting the mechanical properties of solder joints can also facilitate the development of new lead-free solder materials, addressing environmental concerns associated with traditional lead-based solders [25].

5.6 Future Directions and Research Opportunities

Future research should focus on further refining ANN models and exploring new hybrid AI frameworks to enhance prediction accuracy and computational efficiency.

6. CONCLUSION

In conclusion, the use of Artificial Neural Networks for predicting the strength and reliability of Sn-Cu lead-free solder joints have proven to be highly effective, outperforming traditional empirical and FEM methods. The ability of ANNs to model complex mechanical properties and failure mechanisms, combined with the potential of hybrid AI frameworks, offers significant advantages for the electronics industry. Continued research and development in this area will further enhance the predictive capabilities and practical applications of ANNs in solder joint analysis.

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