UNIVERSITI PUTRA MALAYSIA

INTERFACIAL ANALYSIS OF CARBON NANOTUBES-REINFORCED AND GRAPHENE-REINFORCED Sn-1.0Ag-0.5Cu SOLDER ON ELECTROLESS NICKEL/ IMMERSION SILVER SURFACE FINISH

VIDYATHARRAN A/L KRISHNA

INTERFACIAL ANALYSIS OF CARBON NANOTUBES-REINFORCED AND GRAPHENE-REINFORCED Sn-1.0Ag-0.5Cu SOLDER ON ELECTROLESS NICKEL/ IMMERSION SILVER SURFACE FINISH

By

VIDYATHARRAN A/L KRISHNA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Master of Science

November 2020

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

INTERFACIAL ANALYSIS OF CARBON NANOTUBES-REINFORCED AND GRAPHENE-REINFORCED Sn-1.0Ag-0.5Cu SOLDER ON ELECTROLESS NICKEL/ IMMERSION SILVER SURFACE FINISH

By

VIDYATHARRAN A/L KRISHNA

November 2020

Chairperson : Azmah Hanim binti Mohamed Ariff, PhD
Faculty : Engineering

Interconnection material examination of composite solder materials and general comparison of the joints with the solder alloy are fundamental to search for more comparable and dependable alternative to the solder candidate. In this investigation, SAC105 carries two reinforced parameters, carbon nanotubes (CNTs) and graphene nanosheets (GNS), alongside with two different surface finish, electroless nickel/ immersion silver (ENImAg) and copper substrate. This is because the plain SAC105 facing extreme deterioration of IMC formation and weak mechanical strength compared with reinforced SAC105. Thus, evaluation of the intermetallic compound formation and shear strength properties of ENImAg-based Sn-1.0Ag-0.5Cu solder were carried with the addition of carbon nanotubes reinforced solder systems (Sn-1Ag-0.5Cu-xCNT; x = 0.01, 0.05, and 0.1 wt%), and graphene nanosheets reinforced solder systems (Sn-1Ag-0.5Cu-xGNS; x = 0.01, 0.05, and 0.1 wt%), which were completely mixed over the powder metallurgy process. Reflow on the electroless nickel/immersion silver (ENImAg) and copper surface finish were carried at an optimum temperature of 260°C, to analyze the characterization of the intermetallic compound growth and solder joint microstructure among the plain and composite solders with multi surface finishes. By the same token, a single-lap solder joint system was experimented to assess the shear strength of all the solder samples using similar reflow temperature used for the solder joint characterization. In general, the GNSs and CNTs increased the melting point. The highest melting temperatures received from the DSC scan are 233.44°C for 0.1GNSs composite solder and 232.27°C for 0.1CNTs composite solder. Besides that, the wetting angle shown by GNS-based solders reduced more than CNT-based solders. From the IMC thickness result obtained, a slight change within the total intermetallic compound layer growth was detected in the solder joints, where the thinnest IMC thicknesses are 3.35 μm and 2.53 μm recorded for the SAC105-0.1GNS with copper board and SAC105-0.1GNS with ENImAg board respectively among the overall solders compositions, whereas the 0.01CNT-base solders shows the thinnest between

the other CNT compositions, which is 3.61 μm and 2.65 μm for Cu substrate and ENImAg substrate individually. On the contrary, the shear strength properties shown by SAC105-0.01GNS is the best among the rest of the single-lap solder joints board, which is 11.2MPa for Cu-based substrate and 12.11MPa for ENImAg-based substrate. As conclusion, adding the reinforcements to the plain solder improved the wettability, microstructural growth and shear properties, especially with GNS reinforcement samples. Meanwhile, ENImAg surface finish improve the reliability of the solders more than Cu surface finish.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Sarjana Sains

ANALISIS ANTARAMUKA LOGAM PATERI Sn-1.0Ag-0.5Cu DIPERKUAT DENGAN NANOTIUB KARBON DAN GRAFEN DI ATAS KEMASAN PERMUKAAN NIKEL TANPA ELEKTRIK/ REDAMAN PERAK

Oleh

VIDYATHARRAN A/L KRISHNA

November 2020

Pengerusi : Azmah Hanim Mohamed Ariff, PhD
Fakulti : Kejuruteraan

Pemeriksaan bahan sambungan bahan pateri komposit dan perbandingan umum sambungan dengan aloi pateri adalah asas untuk mencari alternatif yang lebih setanding dan boleh dipercayai di antara calon pemateri. Dalam penyelidikan ini, SAC105 membawa dua parameter bertetulang, karbon tiub nano (CNT) dan lembaran kepingan nano grafen (GNS) dengan dua kemasan permukaan yang berbeza, penyaduran nikel tanpa elektrik/ redaman perak (ENImAg) dan substrat tembaga. Ini disebabkan oleh sifat SAC105 yang polos menyebabkan kemerosotan formasi IMC yang teruk dan kekuatan mekanik yang lemah berbanding dengan SAC105 yang diperkuat. Penilaian pembentukan sebatian antara logam dan sifat kekuatan ricih dari aloi pateri Sn-1.0Ag-0.5Cu dikaji dengan sistem pateri bertetulang karbon tiub nano (Sn-1Ag-0.5Cu-xCNT; x = 0.01, 0.05, and 0.1 wt%), dan sistem pateri bertetulang lembaran kepingan nano grafen (Sn-1Ag-0.5Cu-xGNS; x = 0.01, 0.05, and 0.1 wt%) telah dibuat semasa proses kaji logam serbuk. Aliran semula pada papan penyaduran nikel tanpa elektrik/redaman perak (ENImAg) dan permukaan permukaan tembaga dilakukan pada suhu optimum 260°C, untuk menganalisis ciri pertumbuhan sebatian antara logam dan pateri struktur mikro sendi pateri di antara yang polos dan komposit dengan pelbagai kemasan permukaan. Dengan cara yang sama, sistem sendi pateri satu putaran dieksperimen untuk menilai kekuatan ricih semua sampel pateri menggunakan suhu balikan yang sama yang digunakan untuk pencirikan sendi pateri. Secara umum, GNS dan CNT meningkatkan titik lebur. Suhu lebur tertinggi yang diterima dari imbasan DSC ialah 233.44°C untuk pateri komposit 0.1GNSs dan 232.27°C untuk pateri komposit 0.1CNTs. Selain itu, pateri berasaskan GNS mengurangkan sudut pembasahan lebih banyak berbanding pateri berasaskan CNT. Daripada hasil ketebalan IMC yang diperoleh, sedikit perubahan dalam pertumbuhan lapisan kompaun antara bahan dikesan pada sendi pateri, iaitu ketebalan IMC paling tipis adalah 3.35 µm dan 2.53 µm dicatat untuk SAC105-0.1GNS dengan papan tembaga dan SAC105-0.1GNS dengan papan ENImAg masing-masing antara komposisi pateri keseluruhan, sedangkan pateri

asas 0.01CNT menunjukkan yang paling nipis antara komposisi CNT yang lain, iaitu 3.61 µm dan 2.65 µm untuk substrat Cu dan substrat ENImAg secara individu. Sebaliknya, sifat kekuatan ricih yang ditunjukkan oleh SAC105-0.01GNS adalah yang terbaik di antara papan sambungan pateri satu putaran yang lain, iaitu 11.2MPa untuk substrat berasaskan Cu dan 12.11MPa untuk substrat berasaskan ENImAg. Sebagai kesimpulan, penambahan tetulang pada pateri polos meningkatkan kebasahan, pertumbuhan mikro dan sifat ricih, terutamanya pada tetulang GNS. Sementara itu, kemasan permukaan ENImAg memperkaya kebolehpercayaan pateri lebih daripada permukaan Cu.

ACKNOWLEDGEMENT

First and foremost, I would like to sincerely thank my parents, Mr. and Mrs. Krishna for their endless support, financial assistance and heartfelt prayers during the course of my study.

Next, my deepest gratitude to the chairman of my supervisory committee, Dr. Azmah Hanim binti Mohamed Ariff for the limitless effort and excellent guidance throughout the process of completing my research. This investigation was also financially supported by UPM-Grant Putra; UPM/700-2/1/GPBI/2017/9553600 which were introduced by my chairman. Genuinely thankful for the supporting institution, Universiti Putra Malaysia who provided insight and expertise that greatly assisted the research.

Furthermore, I would also like to send my acknowledgement to the members of my supervisory committee, Dr. Khamirul Amin bin Matori for the beneficial comments and supports, and especially Dr. Saliza Azlina binti Osman from Universiti Tun Hussein Onn, for the assistance of treating and coating of electroless nickel/immersion silver (ENImAg) on Cu plate, and for comments that greatly improved the manuscript.

I also like to show my gratitude to Ramanjaly a/p Krishna and Sarwisan a/l Krishna for their effort, encouragement and love in achieving the motive of this study.

Lastly, all those important advices from my friends and family members are heartily valued.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Azmah Hanim Binti Mohamed Ariff, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Khamirul Amin Bin Matori, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

Saliza Azlina Binti Osman, PhD
Senior Lecturer, Ir
Faculty of Engineering
Universiti Tun Hussein Onn
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 08 April 2021

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

mins	Minutes
h	Hours
θ	Degree
%	Percentage
°	Degree
°C	Degree Celsius
N	Newton
nm	Nanometer
µm	Micrometer
mm	Millimeter
rpm	Revolutions Per Minute
wt.%	Weight Percentage
MPa	Mega Pascal
TPa	Tera Pascal
GPa	Giga Pascal
RE	Rare Earth
Sn	Tin
Ag	Silver
Cu	Copper
Ni	Nickel
Pb	Lead
P	Phosphorus
O	Oxygen

C	Carbon
Zn	Zinc
Fe	Iron
Sb	Antimony
Bi	Bismuth
Cd	Cadmium
Al	Aluminum
In	Indium
Si	Silicon
Ti	Titanium
Mn	Manganese
SAC	Sn-Ag-Cu

LIST OF ABBREVIATIONS

SEM	Scanning Electron Microscopy
FESEM	Field Emission Scanning Electron Microscope
TEM	Transmission Electron Microscopy
EDX	Energy Dispersive X-ray
XRD	X-Ray Diffraction
DSC	Differential Scanning Calorimetry
OM	Optical Microscopy
UTM	Universal Testing Machine
IMC	Intermetallic Compound
CNTs	Carbon Nanotubes
GNSs	Graphene Nanosheets
SWCNTs	Single Walled Carbon Nanotubes
MWCNTs	Multi Walled Carbon Nanotubes
MLGNSs	Multilayer Graphene Nanosheets
ENImAg	Electroless Nickel/Immersion Silver
HASL	Hot Air Solder Level
OSP	Organic Solderability Preservative
ENIG	Electroless Nickel/Immersion Gold
ImSn	Immersion Tin
ImAg	Immersion Silver
PCB	Printed Circuit Board
BGA	Ball Grid Array
SMOBC	Solder Mask Over Bare Copper
ISO	International Organization for Standardization

JEDEC	Joint Electronic Device Engineering Council
RoHs	Restriction of Hazardous Substance
WEEE	Waste of Electrical and Equipment
JEITA	Japan Institute of Electronics Industry Technology Association
EPA	Environmental Protection Agency
APR	Advanced Notice of Proposal Rule
TSCA	Toxic Substance Control Act
YS	Yield Strength
UTS	Ultimate Tensile Strength
USS	Ultimate Shear Strength
US	United States
ASTM	American Society for Testing and Materials
RMA	Rosin Mildly Active Flux
CTE	Coefficient of Thermal Expansion

CHAPTER 1

INTRODUCTION

1.1 Background of Research

In the world of electronics and gadgets, solder joint functions as a connecting bridge between the circuit board and electrical components. Since the solder joints have its own breakable characteristics, the features of the intermetallic compounds (IMCs) created during soldering is very important in order to have a lead on achieving the most desirable lead-free solder (Shangguan, 2005). On account of this, solutions have been carried out to overcome the extreme growth of IMC layers. As electrical system keeps advancing and miniaturizing in trend, the need of high robustness and stability is increase as well, thus the interconnection of a solder face difficulties in terms of solder joint reliability. Besides that, suggestions for a suitable solder to replace the lead (Pb) solders ought to require equal or more advanced reliability compare to Sn-Pb solder (Al Athamneh et al., 2020; Chen et al., 2016).

Currently, since conventional lead-free solder technology cannot assure the required joint reliability, scholars have highlighted the addition of elements in lead-free solders. The aim in mind is to enhance in the characterization of interconnection joints. With the addition of reinforcements into a conventional solder, it results in better reliability can be attained. As a result, there are few reinforcements capable of improving the properties of interconnection joints, especially mixture of carbon-based elements on the solder alloy, which can provide a more homogenous distribution among the particles (Chen et al., 2016; El-Daly et al., 2014a). Additionally, carbon nanotubes (CNTs) and graphene nanosheets (GNSs) are attracting the attention of many researchers to explore in the solder field.

Moreover, another significant cause that affects the reliability of solder joints is the Printed Circuit Board (PCB) surface finish as it provides a vital interface during the assemblies between electronic component and the PCB substrate. Functional coatings of solder mask over bare copper (SMOBC) type are generally used for PCB surface finish. SMOBC has two main purposes: to protect the copper circuit and to provide more efficient solderable surface for the components and the board during soldering (Siewiorek et al., 2013). Among all the multi surface finishes, electroless nickel/immersion silver (ENImAg) has an outstanding reliability and gaining momentum in scientific investigations.

1.2 Problem Statement

Evolution has taken place in the technologies of this world and provides a great beneficiary and innovation. Electronics and gadgets productions are one of the main source of this advancement as it became more efficient, easier to handle and miniaturized in this current year. Hence, longer consistency of components in electronics packaging links to more progressive reliability for solder joints (Yoon et al., 2005).

When it comes to low-melting point, good wetting properties and low-cost solder, eutectic tin-lead solder alloy is preferable and broadly used in electronic packaging industry for the past years (Chen et al., 2005). Yet, the utilization of lead in electronics packaging has been to a great extent constrained on the grounds that it is toxic in nature and hazardous to people's health. Thus, legislation to ban lead and supporting the practice of ecological compounds were established (Khodabakhshi et al., 2017).

Solder joints are in control for electrical continuity, heat conduction, mechanical attachment and withstand other external forces depending on the microstructural characteristics. Regarding the production of good quality interconnects, interfacial IMC layer formed in the middle of the solder alloy and surface finish should maintain certain properties (Branzei et al., 2012). It is recalled that, as IMC thickness increases in solder interconnection, the tendency of a solder to become weaker and coarsen is high due to the brittle nature of IMC. Even though lead solders achieve thinner IMCs to meet the requirements of a desirable solder, none of the existing lead-free solders have established to be suitable to substitute the lead-based solders due to the defects developed from disadvantageous IMC growth and weak mechanical properties.

Lately, studies have shown that implanting a secondary phase's reinforcement for lead-free solders develop outstanding properties for the interconnection joints, where it can enhance life span, more homogenous and resist harsh conditions (Nai et al., 2006a). Among various reinforcements, carbon-based material (e.g., carbon nanotube and graphene nanosheet) have attracted a wide number of scholars due to outstanding chemical and physical characteristics. Based on a research done by Kumar et al. (2008b), carbon nanotubes (CNTs) can enhance the melting properties and mechanical strength of SAC solders. Liu et al., (2013) highlighted that the existence of graphene nanosheets (GNSs) as reinforcement can efficiently decrease the coefficient of thermal expansion (CTE), enhance the Ultimate Tensile Strength (UTS) and microhardness.

However, these particular reinforcements have poor wetting properties in SAC solder matrix and frequently noticed to be excluded from molten solder during soldering. To avoid this issue, the addition of metal nanoparticles such as Au, Ag and Ni in the composite solder improves the IMCs during reflow process (Chen et al., 2016). Mokhtari et al. (2012) experimented about the combination of silica nanoparticles with an Au layer, the result highlights that the nanoparticle reinforcement is able to be wetted by molten solder. Similarly, the effect of Ni addition in CNTs increased the microstructural and mechanical properties of solder joint (Yang et al., 2014).

Therefore, altering surface finish in a solder resulting an enhancement in the reliability and mechanical properties of the solder joint. Based on Zeng et al. (2002) investigations, Ni coating on Cu plate offers a flat and uniform surface, particularly on a rough surface. Then, when applied along with Au-finish, it sustains good wettability even after multiple reflows and delivers great strength due to higher mechanical strength and fatigue resistance than Cu. Unfortunately, due to the expensive cost of Au, it is suggested to be replaced with an element that has almost similar properties but with lower price value (Lentz & Assembly, 2018).

Recent survey shows many researchers have investigated the advancement of lead-free solders through CNTs and GNSs reinforcement with multi surface finishes in SAC solder nominees. However, no experiment has yet to be carried on the reinforcements mentioned with electroless nickel/immersion silver (ENImAg) surface finish for SAC105. Thus, this investigation will be conducted to compare and improve the basic properties of SAC105 solder and its reliability.

1.3 Importance of Study

A lifecycle period of solder joints interconnection has brought about huge discussions on the matter of advancement of lead-free solder. While the size of electronic components gets smaller and more efficient, the stress force initiated from surrounding factors during operational period of the components increases. Thus, advancement in this field of knowledge must be highlighted to face the current specifications in the microelectronic industries.

Relating to this, studies have shown that the most preferred solder candidate to replace lead solders are Sn-Ag-Cu (SAC) solders. Moreover, Sn-1.0Ag-0.5Cu (SAC105) has comparatively high melting temperature of 235°C. For this step, soldering is considered as one of the most efficient ways to reducing the exposure old-soldered joints with thermally challenged components, thus improving its lifespan. Besides that, since SAC105 can withstand relatively high temperature, this interconnection joint can be operated in extreme conditions and high temperature applications.

Even though, SAC105 solders have the necessary properties to be a candidate for lead-free soldering, lead solders are still desired compared with the conventional SAC105 solder due to its low reliability in intermetallic growth and mechanical strength. Thus, this study is focused on experimentation and reports on electronic application towards the improvements SAC105, with the assistance of carbon nanotubes (CNTs) and graphene nanosheets (GNSs) as reinforcement, and electroless nickel/immersion silver (ENImAg) as surface finish.

1.4 Objectives

i. To investigate the intermetallic morphology of plain Sn-1.0Ag-0.5Cu (SAC105) solder alloy and SAC105-xCNT/GNS (x = 0.01, 0.05 and 0.1 wt%) composite solders with Cu and ENImAg as surface finish.

ii. To analyze the shear strength of plain Sn-1.0Ag-0.5Cu (SAC105) solder alloy and SAC105-xCNT/GNS (x = 0.01, 0.05 and 0.1 wt%) composite solders with Cu and ENImAg as surface finish.

1.5 Scope of Study

The intermetallic growth and shear strength properties of the solder joints are very significant in relation when it comes to reliability of solder. Therefore, SAC105 reinforced with CNT/GNS were reflowed at 260°C with ENImAg and bare Cu as surface finish. This method is conducted for both the IMC growth test and shear strength analysis, then the results of the composite solders with two different substrates (bare Cu and ENImAg) were compared as-reflowed to ensure the difference in growth of IMC interface and shear strength properties.

1.6 Outline

Chapter one of this research included background studies, problem statement, research objectives and importance of the study. Besides that, the technique and substrates used for the comparison are included in the scope of study. The second chapter of this thesis explains significant reviews of related studies and latest advancement applied and investigated regarding this field. Anything related to lead-free solders are elaborated in this section with the purpose of verifying how this interconnection joints will be evaluated and characterized in this study.

Interpretation from the investigation done via particular steps and procedures for the data collection process are explained in the third chapter. Accordingly, discussion about sample preparation, usage of equipment, and steps taken to collect data are described here. Other than that, formula used for the measurement of IMC growth layer and shear strength data are also presented.

Results interpreted and discussion about the changes occurred in the lead-free solder from this research are shown in Chapter Four of this study. Reasons why a lead-free solder with these particular compositions reacted as such are well explained in this chapter.

Lastly, Chapter Five conclude the entire work of this study, recommendation for the upcoming scholars, and provides also references.

REFERENCES

Abtew, M., & Selvaduray, G. (2000). Lead-free solders in microelectronics. *Materials Science and Engineering: R: Reports, 27*(5), 95-141. https://doi.org/10.1016/S0927-796X(00)00010-3

Adawiyah, M. A.R., & Azlina, O. S. (2017). Solder Volume Effect on Interfacial Reaction between Sn-Ag-Cu/ENImAg Substrate. *Procedia engineering, 184*, 604-610. https://doi.org/10.1016/j.proeng.2017.04.157

Adawiyah, M. A.R., & Azlina, O. S. (2018). Comparative study on the isothermal aging of bare Cu and ENImAg surface finish for Sn-Ag-Cu solder joints. *Journal of Alloys and Compounds, 740*, 958-966. https://doi.org/10.1016/j.jallcom.2018.01.054

Aisha, I. S. R., Ourdjini, A., Hanim, M. A. A., & Azlina, O. S. (2015). Effect of reflow soldering profile on intermetallic compound formation. *International Journal of Computer Applications in Technology, 52*(4), 244-250. https://doi.org/10.1504/IJCAT.2015.073590

Al Athamneh, R., Hani, D. B., Ali, H., & Hamasha, S. (2020). Reliability modeling for aged SAC305 solder joints cycled in accelerated shear fatigue test. *Microelectronics Reliability, 104*, 113507. https://doi.org/10.1016/j.microrel.2019.113507

Anuar, M., & Adawiyah, R. (2017). *Interfacial reaction between SAC305 and SAC405 lead-free solders and electroless nickel/immersion silver (ENImAg) surface finish* [Doctoral Dissertation]. Universiti Tun Hussein Onn Malaysia.

Arfaei, B., Kim, N., & Cotts, E. J. (2012). Dependence of Sn grain morphology of Sn-Ag-Cu solder on solidification temperature. *Journal of electronic materials, 41*(2), 362-374. https://doi.org/10.1007/s11664-011-1756-0

Azlina, O. S., Ourdjini, A., & Ibrahim, M. H. I. (2015). *Comparison between SAC405 lead-free solders and EN (P) EPIG and EN (B) EPIG surface finishes.* Applied Mechanics and Materials, 773–774, 232–236. https://doi.org/10.4028/www.scientific.net/amm.773-774.232

Brady, G. S., Clauser, H. R., & Vaccari, J. A. (1956). *Materials handbook* (Vol. 15). McGraw-hill.

Branzei, M., Plotog, I., Miculescu, F., Varzaru, G., Svasta, P., & Thumm, A. (2012). *Solder joints properties as function of multiple reflow vapor phase soldering process* [Paper presentation]. 2012 35th International Spring Seminar on Electronics Technology. Bad Aussee, Austria. https://doi.org/10.1109/ISSE.2012.6273127.

Bunce, M., Clark, L., & Swanson, J. (2017). *Achieving a Successful ENIG Finished PCB Under Revision a of IPC 4552 MacDermid Enthone* [Paper Presentation]. Proceedings of SMTA International, Rosemont, IL, USA. https://electronics.macdermidenthone.com/application/files/4815/0662/8355/Achieving_a_Successful_ENIG_Finished_PCB_Under_REvision_A_of_IPC_4552_Bunce_Martin_SMTA_2017.pdf

Chang, D. F., Bai, F., Wang, Y. P., & Hsiao, C. S. (2004). *The study of OSP as reliable surface finish of BGA substrate* [Paper Presentation]. Proceedings of 6th Electronics Packaging Technology Conference (EPTC 2004)(IEEE Cat. No. 04EX971), Singapore. https://doi.org/10.1109/EPTC.2004.1396594.

Chen, B. L., & Li, G. Y. (2004). Influence of Sb on IMC growth in Sn–Ag–Cu–Sb Pb-free solder joints in reflow process. *Thin Solid Films, 462*, 395-401. https://doi.org/10.1016/j.tsf.2004.05.063

Chen, G., Wu, F., Liu, C., Silberschmidt, V. V., & Chan, Y. C. (2016). Microstructures and properties of new Sn–Ag–Cu lead-free solder reinforced with Ni-coated graphene nanosheets. *Journal of Alloys and Compounds, 656*, 500-509. https://doi.org/10.1016/j.jallcom.2015.09.178

Chen, X., Yu, D. H., & Kim, K. S. (2005). Experimental study on ratcheting behavior of eutectic tin–lead solder under multiaxial loading. *Materials Science and Engineering: A, 406*(1-2), 86-94. https://doi.org/10.1016/j.msea.2005.06.013

Cheng, F., Gao, F., Zhang, J., Jin, W., & Xiao, X. (2011). Tensile properties and wettability of SAC0307 and SAC105 low Ag lead-free solder alloys. *Journal of materials science, 46*(10), 3424-3429. https://doi.org/10.1007/s10853-010-5231-8

Cheng, H. K., Huang, C. W., Lee, H., Wang, Y. L., Liu, T. F., & Chen, C. M. (2015). Interfacial reactions between Cu and SnAgCu solder doped with minor Ni. *Journal of Alloys and Compounds, 622*, 529-534. https://doi.org/10.1016/j.jallcom.2014.10.121

Choi, W. K., Kang, S. K., & Shih, D.-Y. (2002). A study of the effects of solder volume on the interfacial reactions in solder joints using the differential scanning calorimetry technique. *Journal of electronic materials, 31*(11), 1283-1291. https://doi.org/10.1007/s11664-002-0022-x

Choubey, A., Yu, H., Osterman, M., Pecht, M., Yun, F., Yonghong, L., & Ming, X. (2008). Intermetallics characterization of lead-free solder joints under isothermal aging. *Journal of electronic materials, 37*(8), 1130-1138. https://doi.org/10.1007/s11664-008-0466-8

Chuang, C. L., Tsao, L. C., Lin, H. K., & Feng, L. P. (2012). Effects of small amount of active Ti element additions on microstructure and property of Sn3. 5Ag0. 5Cu solder. *Materials Science and Engineering: A, 558*, 478-484. https://doi.org/10.1016/j.msea.2012.08.031

Dele-Afolabi, T. T., Hanim, M. A. A., Calin, R., & Ilyas, R. A. (2020). Microstructure evolution and hardness of MWCNT-reinforced Sn-5Sb/Cu composite solder joints under different thermal aging conditions. *Microelectronics Reliability, 110*, 113681. https://doi.org/10.1016/j.microrel.2020.113681

Dele-Afolabi, T. T., Hanim, M. A. A., Norkhairunnisa, M., Suraya, M. T., & Yusoff, H. M. (2017). *Influence of multi-walled carbon nanotubes on melting temperature and microstructural evolution of Pb-free Sn-5Sb/Cu solder joint.* IOP Conference Series: Materials Science and Engineering, *238*(1), 012010.

Dele-Afolabi, T. T., Hanim, M. A. A., Norkhairunnisa, M., Yusoff, H. M., & Suraya, M. T. (2015). Investigating the effect of isothermal aging on the morphology and shear strength of Sn-5Sb solder reinforced with carbon nanotubes. *Journal of Alloys and Compounds, 649*, 368-374. https://doi.org/10.1016/j.jallcom.2015.07.036

Dele-Afolabi, T. T., Hanim, M. A. A., Ojo-Kupoluyi, O. J., & Calin, R. (2019). Impact of different isothermal aging conditions on the IMC layer growth and shear strength of MWCNT-reinforced Sn–5Sb solder composites on Cu substrate. *Journal of Alloys and Compounds, 808*, 151714. https://doi.org/10.1016/j.jallcom.2019.151714

Dillard, D. A. (2010). *Advances in structural adhesive bonding*. Elsevier.

El-Daly, A. A., Al-Ganainy, G. S., Fawzy, A., & Younis, M. J. (2014a). Structural characterization and creep resistance of nano-silicon carbide reinforced Sn–1.0 Ag–0.5 Cu lead-free solder alloy. *Materials & Design, 55*, 837-845. https://doi.org/10.1016/j.matdes.2013.10.043

El-Daly, A. A., Hammad, A. A., Al-Ganainy, G. S., & Ragab, M. (2014b). Influence of Zn addition on the microstructure, melt properties and creep behavior of low Ag-content Sn–Ag–Cu lead-free solders. *Materials Science and Engineering: A, 608*, 130-138. https://doi.org/10.1016/j.msea.2014.04.070

El-Daly, A. A., Hammad, A. E., Fawzy, A., & Nasrallh, D. A. (2013). Microstructure, mechanical properties, and deformation behavior of Sn–1.0 Ag–0.5 Cu solder after Ni and Sb additions. *Materials & Design, 43*, 40-49. https://doi.org/10.1016/j.matdes.2012.06.058

Esfe, M. H., Saedodin, S., Yan, W. M., Afrand, M., & Sina, N. (2016). Study on thermal conductivity of water-based nanofluids with hybrid suspensions of CNTs/Al 2 O 3 nanoparticles. *Journal of Thermal Analysis and Calorimetry, 124*(1), 455-460. https://doi.org/10.1007/s10973-015-5104-0

Fathian, Z., Maleki, A., & Niroumand, B. (2017). Synthesis and characterization of ceramic nanoparticles reinforced lead-free solder. *Ceramics International, 43*(6), 5302-5310. https://doi.org/10.1016/j.ceramint.2017.01.067

Ganesan, S., & Pecht, M. G. (2006). *Lead-free electronics*. John Wiley & Sons.

Geim, A. K. (2009). Graphene: status and prospects. *science, 324*(5934), 1530-1534. https://doi.org//10.1126/science.1158877

Ghamarian, N. (2017). *Characterization Of Multi-Wall Carbon Nanotube/Multilayer Graphene Fibre-Reinforced Solder Alloy Composites.* [Doctoral Dissertation]. Universiti Putra Malaysia.

Ghamarian, N., Hanim, M. A., Zainal, Z., & Lim, H. Shear Strength and Melting Behavior of Eutectic Bi-Ag Solder Alloy Reinforced with Multi-Wall Carbon Nanotube and Multi-Layer Graphene. *First Published in 1 July 2019 All right reserved No part of this publication may be reproduced, stored in a retrieval system of transmitted, in any form of by any means, electronic, mechanical, photocopying, recording of otherwise, without the prior permission of the copyright owner.*, 1.

Guo, F., Choi, S., Lucas, J. P., & Subramanian, K. N. (2000). Effects of reflow on wettability, microstructure and mechanical properties in lead-free solders. *Journal of electronic materials, 29*(10), 1241-1248. https://doi.org/10.1007/s11664-000-0019-2

Hamilton, C., Kelly, M., & Snugovsky, P. (2007). Effects of SAC Alloy Copper Dissolution Rates on PTH Processes-High copper dissolution rates of SAC 305/405 alloys are the driving factor for changing the alloy for solder fountain rework, a change. *Circuits Assembly, 18*(6), 34-37.

Hammad, A. E. (2018). Enhancing the ductility and mechanical behavior of Sn-1.0 Ag-0.5 Cu lead-free solder by adding trace amount of elements Ni and Sb. *Microelectronics Reliability, 87*, 133-141. https://doi.org/10.1016/j.microrel.2018.06.015

Han, Y., Gao, Y., Jing, H., Wei, J., Zhao, L., & Xu, L. (2020). A modified constitutive model of Ag nanoparticle-modified graphene/Sn–Ag–Cu/Cu solder joints. *Materials Science and Engineering: A*, 139080.

Han, Y. D., Jing, H. Y., Nai, S. M. L., Xu, L. Y., Tan, C. M., & Wei, J. (2012). Interfacial reaction and shear strength of Ni-coated carbon nanotubes reinforced Sn–Ag–Cu solder joints during thermal cycling. *Intermetallics, 31*, 72-78. https://doi.org/10.1016/j.intermet.2012.06.002

Han, Y. D., Nai, S. M. L., Jing, H. Y., Xu, L. Y., Tan, C. M., & Wei, J. (2011). Development of a Sn–Ag–Cu solder reinforced with Ni-coated carbon nanotubes. *Journal of Materials Science: Materials in Electronics, 22*(3), 315-322. https://doi.org/10.1007/s10854-010-0135-6

Höper, R., Workman, R. K., Chen, D., Sarid, D., Yadav, T., Withers, J. C., & Loutfy, R. O. (1994). Single-shell carbon nanotubes imaged by atomic force microscopy. *Surface science, 311*(3), L731-L736. https://doi.org/10.1016/0039-6028(94)91417-6

Hu, X., Chan, Y. C., Zhang, K., & Yung, K. C. (2013). Effect of graphene doping on microstructural and mechanical properties of Sn–8Zn–3Bi solder joints together with electromigration analysis. *Journal of Alloys and Compounds, 580*, 162-171. https://doi.org/10.1016/j.jallcom.2013.05.124

Huang, Y., Xiu, Z., & Tian, Y. (2016a). *Sn-3.0 Ag-0.5 Cu composite solder reinforced by multilayer graphene* [Paper Presentation]. 2016 China Semiconductor Technology International Conference (CSTIC), Shanghai, China. https://doi.org/10.1109/CSTIC.2016.7463949.

Huang, Y., Xiu, Z., Wu, G., Tian, Y., & He, P. (2016b). Sn–3.0 Ag–0.5 Cu nanocomposite solders reinforced by graphene nanosheets. *Journal of Materials Science: Materials in Electronics, 27*(7), 6809-6815. https://doi.org/10.1007/s10854-016-4631-1

Huang, Y., Xiu, Z., Wu, G., Tian, Y., He, P., Gu, X., & Long, W. (2016c). Improving shear strength of Sn-3.0 Ag-0.5 Cu/Cu joints and suppressing intermetallic compounds layer growth by adding graphene nanosheets. *Materials Letters, 169*, 262-264. https://doi.org/10.1016/j.matlet.2016.01.125

Iijima, S. (1991). Helical microtubules of graphitic carbon. *Nature, 354*, 56-58. https://doi.org/10.1038/354056a0

Jing, H. Y., Guo, H. J., Wang, L. X., Wei, J., Xu, L. Y., & Han, Y. D. (2017). Influence of Ag-modified graphene nanosheets addition into Sn–Ag–Cu solders on the formation and growth of intermetallic compound layers. *Journal of Alloys and Compounds, 702*, 669-678. https://doi.org/10.1016/j.jallcom.2017.01.286

Karousis, N., Tagmatarchis, N., & Tasis, D. (2010). Current progress on the chemical modification of carbon nanotubes. *Chemical reviews, 110*(9), 5366-5397. https://doi.org/10.1021/cr100018g

Khodabakhshi, F., Sayyadi, R., & Javid, N. S. (2017). Lead free Sn-Ag-Cu solders reinforced by Ni-coated graphene nanosheets prepared by mechanical alloying: Microstructural evolution and mechanical durability. *Materials Science and Engineering: A, 702*, 371-385. https://doi.org/10.1016/j.msea.2017.07.024

Kim, J., Back, J. H., Jung, S. B., & Yoon, J. W. (2019). Effects of Ni layer thickness of thin-ENEPIG surface finishes on the interfacial reactions and shear strength of Sn-3.0 Ag–0.5 Cu solder joints during aging. *Journal of Materials Science: Materials in Electronics, 30*(14), 12911-12923. https://doi.org/10.1007/s10854-019-01653-x

Kim, K. S., Huh, S. H., & Suganuma, K. (2002). Effects of cooling speed on microstructure and tensile properties of Sn–Ag–Cu alloys. *Materials Science and Engineering: A, 333*(1-2), 106-114. https://doi.org/10.1016/S0921-5093(01)01828-7

Kim, K. S., Huh, S. H., & Suganuma, K. (2003). Effects of intermetallic compounds on properties of Sn–Ag–Cu lead-free soldered joints. *Journal of Alloys and Compounds, 352*(1-2), 226-236. https://doi.org/10.1016/S0925-8388(02)01166-0

Kotadia, H. R., Howes, P. D., & Mannan, S. H. (2014). A review: On the development of low melting temperature Pb-free solders. *Microelectronics Reliability, 54*(6-7), 1253-1273. https://doi.org/10.1016/j.microrel.2014.02.025

Kumar, K. M., Kripesh, V., & Tay, A. A. O. (2008a). Influence of single-wall carbon nanotube addition on the microstructural and tensile properties of Sn–Pb solder alloy. *Journal of Alloys and Compounds, 455*(1-2), 148-158. https://doi.org/10.1016/j.jallcom.2007.01.045

Kumar, K. M., Kripesh, V., & Tay, A. A. O. (2008b). Single-wall carbon nanotube (SWCNT) functionalized Sn–Ag–Cu lead-free composite solders. *Journal of Alloys and Compounds, 450*(1-2), 229-237. https://doi.org/10.1016/j.jallcom.2006.10.123

Kumar, K. M., Kripesh, V., & Tay, A. A. (2018). Properties of 63Sn-37Pb and Sn-3.8 Ag-0.7 Cu Solders Reinforced With Single-Wall Carbon Nanotubes. In J. Morris (Eds), *Nanopackaging* (pp. 649-676). Springer. https://doi.org/10.1007/978-3-319-90362-0_20

Lee, C., Wei, X., Kysar, J. W., & Hone, J. (2008). Measurement of the elastic properties and intrinsic strength of monolayer graphene. *Science, 321*(5887), 385-388. https://doi.org/10.1126/science.1157996

Lee, N. C. (2002). *Reflow soldering processes*. Elsevier.

Lee, Y. H., & Lee, H. T. (2007). Shear strength and interfacial microstructure of Sn–Ag–xNi/Cu single shear lap solder joints. *Materials Science and Engineering: A, 444*(1-2), 75-83. https://doi.org/10.1016/j.msea.2006.08.065

Lentz, T., & Assembly, F. (2018). *How Does Surface Finish Affect Solder Paste Performance?* [Paper Presentation]. Proceedings of SMTA International.

Li, Y., Luo, K., Lim, A. B. Y., Chen, Z., Wu, F., & Chan, Y. C. (2016). Improving the mechanical performance of Sn57. 6Bi0. 4Ag solder joints on Au/Ni/Cu pads during aging and electromigration through the addition of tungsten (W) nanoparticle reinforcement. *Materials Science and Engineering: A, 669*, 291-303. https://doi.org/10.1016/j.msea.2016.05.092

Li, Y., Wang, S., Wang, Q., & Xing, M. (2018). A comparison study on mechanical properties of polymer composites reinforced by carbon nanotubes and graphene sheet. *Composites Part B: Engineering, 133*, 35-41. https://doi.org/10.1016/j.compositesb.2017.09.024

Liu, X. D., Han, Y. D., Jing, H. Y., Wei, J., & Xu, L. Y. (2013). Effect of graphene nanosheets reinforcement on the performance of Sn□ Ag□ Cu lead-free solder. *Materials Science and Engineering: A, 562*, 25-32. https://doi.org/10.1016/j.msea.2012.10.079

Long, E., & Toscano, L. (2013). Electroless Nickel/Immersion Silver—A new surface finish PCB applications. *Metal Finishing, 111*(1), 12-19. https://doi.org/10.1016/S0026-0576(13)70171-5

Ma, H. L., Jia, Z., Lau, K. t., Li, X., Hui, D., & Shi, S. q. (2017a). Enhancement on mechanical strength of adhesively-bonded composite lap joints at cryogenic environment using coiled carbon nanotubes. *Composites Part B: Engineering, 110*, 396-401. https://doi.org/10.1016/j.compositesb.2016.11.019

Ma, X., Qian, Y., & Yoshida, F. (2002). Effect of La on the Cu–Sn intermetallic compound (IMC) growth and solder joint reliability. *Journal of Alloys and Compounds, 334*(1-2), 224-227. https://doi.org/10.1016/S0925-8388(01)01747-9

Ma, Y., Li, X., Yang, L., Zhou, W., Wang, M., Zhu, W., & Wu, P. (2017b). Effects of graphene nanosheets addition on microstructure and mechanical properties of SnBi solder alloys during solid-state aging. *Materials Science and Engineering: A, 696*, 437-444. https://doi.org/10.1016/j.msea.2017.04.105

Ma, Y., Li, X., Zhou, W., Yang, L., & Wu, P. (2017c). Reinforcement of graphene nanosheets on the microstructure and properties of Sn58Bi lead-free solder. *Materials & Design, 113*, 264-272. https://doi.org/10.1016/j.matdes.2016.10.034

Messler, R. W. (2004). *Joining of materials and structures: from pragmatic process to enabling technology*. Butterworth-Heinemann.

Miller, C. M., Anderson, I. E., & Smith, J. F. (1994). A viable tin-lead solder substitute: Sn-Ag-Cu. *Journal of Electronic Materials, 23*(7), 595-601. https://doi.org/10.1007/BF02653344

Mohd Salleh, M., McDonald, S., & Nogita, K. (2013). *Non-metal reinforced lead-free composite solder fabrication methods and its reinforcing effects to the suppression of intermetallic formation: short review.* Applied Mechanics and Materials, 421, 260-266. https://doi.org/10.4028/www.scientific.net/amm.421.260.

Mohd Salleh, M. A. A. ., McDonald, S. D., Gourlay, C. M., Yasuda, H., & Nogita, K. (2016). Suppression of Cu6Sn5 in TiO2 reinforced solder joints after multiple reflow cycles. *Materials & Design, 108*, 418-428. https://doi.org/10.1016/j.matdes.2016.06.121

Mokhtari, O., Roshanghias, A., Ashayer, R., Kotadia, H. R., Khomamizadeh, F., Kokabi, A. H., Clode, M. P., Miodownik, M., &Mannan, S. H. (2012).

Disabling of nanoparticle effects at increased temperature in nanocomposite solders. *Journal of electronic materials, 41*(7), 1907-1914. https://doi.org/10.1007/s11664-012-1976-y

Monthioux, M., & Kuznetsov, V. L. (2006). Who should be given the credit for the discovery of carbon nanotubes? *Carbon, 44*(9), 1621-1623.

Nai, S. M. L., Wei, J., & Gupta, M. (2006a). Improving the performance of lead-free solder reinforced with multi-walled carbon nanotubes. *Materials Science and Engineering: A, 423*(1-2), 166-169. https://doi.org/10.1016/j.msea.2005.10.072Nai, S. M. L., Wei, J., & Gupta, M. (2006b). Influence of ceramic reinforcements on the wettability and mechanical properties of novel lead-free solder composites. *Thin Solid Films, 504*(1-2), 401-404. https://doi.org/10.1016/j.tsf.2005.09.057

Nai, S. M. L., Wei, J., & Gupta, M. (2006c). Lead-free solder reinforced with multiwalled carbon nanotubes. *Journal of electronic materials, 35*(7), 1518-1522. https://doi.org/10.1007/s11664-006-0142-9

Nai, S. M. L., Wei, J., & Gupta, M. (2008). Effect of carbon nanotubes on the shear strength and electrical resistivity of a lead-free solder. *Journal of electronic materials, 37*(4), 515-522. https://doi.org/10.1007/s11664-008-0379-6

Niranjani, V., Venkateswarlu, P., Singh, V., Rao, B. C., & Kamat, S. (2018). Effect of Gold Addition on the Microstructure and Mechanical Properties of Sn–3.8 Ag–0.7 Cu Lead-Free Solder Alloy. *Transactions of the Indian Institute of Metals, 71*(6), 1497-1505.

Nogita, K., & Nishimura, T. (2008). Nickel-stabilized hexagonal (Cu, Ni) 6Sn5 in Sn–Cu–Ni lead-free solder alloys. *Scripta Materialia, 59*(2), 191-194. https://doi.org/10.1016/j.scriptamat.2008.03.002

Peng, H., LÜ, X. C., LIN, T. S., LI, H. X., Jing, A., Xin, M. A., Feng, J. C., Zhang, Y., Li, Q., Qian, Y. Y. (2012). Improvement of mechanical properties of Sn–58Bi alloy with multi-walled carbon nanotubes. *Transactions of Nonferrous Metals Society of China, 22*, s692-s696. https://doi.org/10.1016/S1003-6326(12)61788-9

Prasantha, K. H. G. & Xavior, A. (2018). Processing of Graphene/CNT-Metal Powder. In A. A. Cavalheiro (Eds), *Powder Technology* (pp. 45-64). IntechOpen.

Saleh, T. A., Majeed, S., Nayak, A., & Bhushan, B. (2017). Principles and advantages of microwave-assisted methods for the synthesis of nanomaterials for water purification. *Advanced Nanomaterials for Water Engineering, Treatment, and Hydraulics* (pp. 40-57). IGI Global.

Shangguan, D. (2005). *Lead-free solder interconnect reliability*. ASM international.

Shen, Y.-L., Chawla, N., Ege, E. S., & Deng, X. (2005). Deformation analysis of lap-shear testing of solder joints. *Acta materialia, 53*(9), 2633-2642. https://doi.org/10.1016/j.actamat.2005.02.024

Shnawah, D. A., Sabri, M. F. M., & Badruddin, I. A. (2012). A review on thermal cycling and drop impact reliability of SAC solder joint in portable electronic products. *Microelectronics Reliability, 52*(1), 90-99. https://doi.org/10.1016/j.microrel.2011.07.093

Siewiorek, A., Kudyba, A., Sobczak, N., Homa, M., Huber, Z., Adamek, Z., & Wojewoda-Budka, J. (2013). Effects of PCB substrate surface finish and flux on solderability of lead-free SAC305 alloy. *Journal of Materials Engineering and Performance, 22*(8), 2247-2252. https://doi.org/10.1007/s11665-013-0492-4

Sonawane, P. D., & Raja, V. K. B. (2019). Advances in Lead-Free Solders. *Int. J. of Mech. Engg. and Tech., 10*(2), 520-526. http://www.iaeme.com/ijmet/issues.asp?JType=IJMET&VType=10&IType=02

Sun, L., Zhang, L., Zhong, S. J., Ma, J., & Bao, L. (2015). Reliability study of industry Sn3. 0Ag0. 5Cu/Cu lead-free soldered joints in electronic packaging. *Journal of Materials Science: Materials in Electronics, 26*(11), 9164-9170. https://doi.org/10.1007/s10854-015-3606-y

Tang, Y., Luo, S. M., Li, Z. H., Hou, C. J., & Li, G. Y. (2018). Morphological Evolution and Growth Kinetics of Interfacial Cu 6 Sn 5 and Cu 3 Sn Layers in Low-Ag Sn-0.3 Ag-0.7 Cu-xMn/Cu Solder Joints During Isothermal Ageing. *Journal of electronic materials, 47*(10), 5913-5929. https://doi.org/10.1007/s11664-018-6481-5

Toscano, L. M., & Long, E. (2014). *A new surface finish for the electronics industry: Electroless nickel/immersion silver* [Paper Presentation]. 2014 9th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT), Taipei, Taiwan. https://doi.org/10.1109/IMPACT.2014.7048458.

Tsao, L. C., & Chang, S. Y. (2010). Effects of nano-TiO2 additions on thermal analysis, microstructure and tensile properties of Sn3. 5Ag0. 25Cu solder. *Materials & Design, 31*(2), 990-993. https://doi.org/10.1016/j.matdes.2009.08.008

Tsao, L. C., Chang, S. Y., Lee, C. L., Sun, W. H., & Huang, C. H. (2010). Effects of nano-Al2O3 additions on microstructure development and hardness of Sn3. 5Ag0. 5Cu solder. *Materials & Design, 31*(10), 4831-4835. https://doi.org/10.1016/j.matdes.2010.04.033

Tu, K.-N. (2007). *Solder joint technology* (Vol. 117). Springer.

Tyson, W. R., & Miller, W. A. (1977). Surface free energies of solid metals: Estimation from liquid surface tension measurements. *Surface science, 62*(1), 267-276. https://doi.org/10.1016/0039-6028(77)90442-3

Wang, H., Hu, X., & Jiang, X. (2020). Effects of Ni modified MWCNTs on the microstructural evolution and shear strength of Sn-3.0 Ag-0.5 Cu composite solder joints. *Materials Characterization*, 163, 110287. https://doi.org/10.1016/j.matchar.2020.110287

Wang, W., Choubey, A., Azarian, M. H., & Pecht, M. (2009). An Assessment of Immersion Silver Surface Finish for Lead-Free Electronics. *Journal of electronic materials, 38*(6), 815-827. https://doi.org/10.1007/s11664-009-0761-z

Wang, Y. W., Chang, C. C., & Kao, C. R. (2009). Minimum effective Ni addition to SnAgCu solders for retarding Cu3Sn growth. *Journal of Alloys and Compounds, 478*(1-2), L1-L4. https://doi.org/10.1016/j.jallcom.2008.11.027

Wang, Y., Zhao, X., Xie, X., Gu, Y., & Liu, Y. (2015). Effects of nano-SiO 2 particles addition on the microstructure, wettability, joint shear force and the interfacial IMC growth of Sn3. 0Ag0. 5Cu solder. *Journal of Materials Science: Materials in Electronics, 26*(12), 9387-9395. https://doi.org/10.1007/s10854-015-3151-8

Xu, K. K., Zhang, L., Sun, L., Jiang, N., Zhao, M., & Xiong, M. Y. (2020). The influence of carbon nanotubes on the properties of Sn solder. *MATERIALS TRANSACTIONS, 61*(4), 718-722.

Xu, L., Robson, J. D., Wang, L., & Prangnell, P. B. (2018). The influence of grain structure on intermetallic compound layer growth rates in Fe-Al dissimilar welds. *Metallurgical and Materials Transactions A, 49*(2), 515-526. https://doi.org/10.1007/s11661-017-4352-y

Xu, S., Chan, Y. C., Zhang, K., & Yung, K. C. (2014). Interfacial intermetallic growth and mechanical properties of carbon nanotubes reinforced Sn3. 5Ag0. 5Cu solder joint under current stressing. *Journal of Alloys and Compounds, 595*, 92-102. https://doi.org/10.1016/j.jallcom.2014.01.083

Yakymovych, A., Plevachuk, Y., Švec, P., Janičkovič, D., Šebo, P., Beronská, N., Roshanghias, A., &Ipser, H. (2016). Morphology and shear strength of lead-free solder joints with Sn3. 0Ag0. 5Cu solder paste reinforced with ceramic nanoparticles. *Journal of electronic materials, 45*(12), 6143-6149. https://doi.org/10.1007/s11664-016-4832-7

Yang, L., Liu, H., & Zhang, Y. (2018). Study on the Tensile Creep Behavior of Carbon Nanotubes-Reinforced Sn-58Bi Solder Joints. *Journal of electronic materials, 47*(1), 662-671. https://doi.org/10.1007/s11664-017-5741-0

Yang, W., Lv, Y., Zhang, X., Wei, X., Li, Y., & Zhan, Y. (2020). Influence of graphene nanosheets addition on the microstructure, wettability, and mechanical properties of Sn-0.7 Cu solder alloy. *Journal of Materials Science: Materials in Electronics, 31*(17), 14035-14046. https://doi.org/10.1007/s10854-020-03920-8

Yang, Y. (2017). *Failure analysis for bad wetting on HASL PCB* [Paper Presentation]. 2017 18th International Conference on Electronic Packaging Technology (ICEPT), Harbin. https://doi.org/10.1109/ICEPT.2017.8046421.

Yang, Z., Zhou, W., & Wu, P. (2014). Effects of Ni-coated carbon nanotubes addition on the microstructure and mechanical properties of Sn–Ag–Cu solder alloys. *Materials Science and Engineering: A, 590*, 295-300. https://doi.org/10.1016/j.msea.2013.10.008

Yin, L., Zhang, Z., Zuo, C., Fang, N., Yao, Z., & Su, Z. (2019). Microstructures and properties of Sn–0.3 Ag–0.7 Cu solder doped with graphene nanosheets. *Journal of Materials Science: Materials in Electronics*, 31, 1861-1867. https://doi.org/10.1007/s10854-019-02705-y

Yoon, J. W., Kim, S. W., & Jung, S. B. (2004). Effect of reflow time on interfacial reaction and shear strength of Sn–0.7 Cu solder/Cu and electroless Ni–P BGA joints. *Journal of Alloys and Compounds, 385*(1-2), 192-198. https://doi.org/10.1016/j.jallcom.2004.05.009

Yoon, J. W., Kim, S. W., & Jung, S. B. (2005). IMC morphology, interfacial reaction and joint reliability of Pb-free Sn–Ag–Cu solder on electrolytic Ni BGA substrate. *Journal of Alloys and Compounds, 392*(1-2), 247-252. https://doi.org/10.1016/j.jallcom.2004.09.045

Yoon, J. W., Noh, B. I., Kim, B. K., Shur, C. C., & Jung, S. B. (2009). Wettability and interfacial reactions of Sn–Ag–Cu/Cu and Sn–Ag–Ni/Cu solder joints. *Journal of Alloys and Compounds, 486*(1-2), 142-147. https://doi.org/10.1016/j.jallcom.2009.06.159

Yuan, H., Xiong, Y., Luo, G., Li, M., Shen, Q., & Zhang, L. (2016). Microstructure and electrical conductivity of CNTs/PMMA nanocomposite foams foaming by supercritical carbon dioxide. *Journal of Wuhan University of Technology-Mater. Sci. Ed., 31*(2), 481-486. https://doi.org/10.1007/s11595-016-1395-7

Zeng, K., Vuorinen, V., & Kivilahti, J. K. (2002). Interfacial reactions between lead-free SnAgCu solder and Ni (P) surface finish on printed circuit boards. *IEEE Transactions on Electronics Packaging Manufacturing, 25*(3), 162-167. https://doi.org/10.1109/TEPM.2002.801648.

Zhu, Y., Murali, S., Cai, W., Li, X., Suk, J. W., Potts, J. R., & Ruoff, R. S. (2010). Graphene and graphene oxide: synthesis, properties, and applications. *Advanced materials, 22*(35), 3906-3924. https://doi.org/10.1002/adma.201001068

Zhu, Z., Chan, Y. C., Chen, Z., Gan, C. L., & Wu, F. (2018). Effect of the size of carbon nanotubes (CNTs) on the microstructure and mechanical strength of CNTs-doped composite Sn0. 3Ag0. 7Cu-CNTs solder. *Materials Science and Engineering: A, 727*, 160-169. https://doi.org/10.1016/j.msea.2018.05.002

Zubair, M. (2013). *Modification of styrene-methyl meth acrylate copolymer in the presence of pristine and modified graphene by using microwave irradiation* [Master Thesis]. King Fahd University of Petroleum and Minerals (Saudi Arabia).

APPENDICES

APPENDIX A

Wetting Angle Data for Cu substrate

S/N	SAC105	SAC105-0.01GNS	SAC105-0.05GNS	SAC105-0.1GNS	SAC105-0.01CNT	SAC105-0.05CNT	SAC105-0.1CNT
1	57.53	44.53	21.15	15.23	27.84	30.95	32.3
2	61.9	47.96	18.46	13.09	14.39	32.64	27.92
3	47.51	36.52	26.53	19.41	22.97	25.57	34.49
4	43.1	35.03	29.22	21.50	9.52	23.88	25.73
Mean	52.5	41.01	23.84	17.32	18.68	28.26	30.11
Standard deviation	8.6971	6.2347	4.9112	3.8341	8.2587	4.1969	3.9984
Standard error	4.3486	3.1173	2.4556	1.9171	4.1294	2.0984	1.9992

Wetting Angle Data for ENImAg substrate

S/N	SAC105	SAC105-0.01GNS	SAC105-0.05GNS	SAC105-0.1GNS	SAC105-0.01CNT	SAC105-0.05CNT	SAC105-0.1CNT
1	51.77	39.21	32.45	12.02	8.95	31.69	39.33
2	43.85	32.95	24.15	14.11	17.01	39.97	44.41
3	56.19	28.52	34.95	7.90	20.74	42.73	40.69
4	39.43	42.60	26.97	5.81	4.98	34.45	45.77
Mean	47.81	35.82	29.63	9.96	12.92	37.21	42.55
Standard deviation	7.5677	6.2978	4.9451	3.7830	7.2269	5.0390	3.036
Standard error	3.7839	3.1489	2.4725	1.8915	3.6135	2.5195	1.5181

APPENDIX B

Data for Total Intermetallic Compound (IMC) Layer for Solders with Cu Substrate

S/N	SAC105	SAC105-0.01GNS	SAC105-0.05GNS	SAC105-0.1GNS	SAC105-0.01CNT	SAC105-0.05CNT	SAC105-0.1CNT
1	5.5388	4.0038	3.9758	3.5887	3.4174	4.2124	4.6909
2	4.9214	3.7848	3.5462	3.1167	3.8048	3.9094	4.1763
Mean	5.2301	3.8943	3.7610	3.3527	3.6111	4.0609	4.4336
Standard deviation	0.4366	0.1549	0.3038	0.3338	0.2739	0.2143	0.3639
Standard error	0.3087	0.0693	0.1359	0.1493	0.1225	0.0958	0.1627

Data for Total Intermetallic Compound (IMC) Layer for Solders with ENImAg Substrate

S/N	SAC105	SAC105-0.01GNS	SAC105-0.05GNS	SAC105-0.1GNS	SAC105-0.01CNT	SAC105-0.05CNT	SAC105-0.1CNT
1	2.7019	2.8004	2.7699	2.3611	2.5642	2.7844	2.7814
2	3.2591	2.7478	2.6345	2.7063	2.7414	2.8786	3.0424
Mean	2.9805	2.7741	2.7022	2.5337	2.6528	2.8314	2.9119
Standard deviation	0.3940	0.0372	0.0957	0.2441	0.1253	0.0665	0.1846
Standard error	0.2786	0.0166	0.0428	0.1092	0.0560	0.0297	0.0825

APPENDIX C

Shear Force (N) Data for Cu Substrate

S/N (Force)	SAC105	SAC105-0.01GNS	SAC105-0.05GNS	SAC105-0.1GNS	SAC105-0.01CNT	SAC105-0.05CNT	SAC105-0.1CNT
1	957.7	1453.1	1080.2	1006.5	1207.8	998.8	591.8
2	540.1	1010.9	612.7	1172.6	1041.7	1378.3	408.1
3	1184.7	1125.3	931.7	495	569.8	1251.8	1151.7
4	331.1	1338.7	464.2	661.1	735.9	872.3	968
Mean	757.9	1232	772.2	833.8	888.8	1125.3	779.9
Standard deviation	391.237	200.453	283.206	310.497	295.438	230.956	340.208
Standard error	195.613	100.221	141.603	155.243	144.419	115.478	170.104

Shear Stress (MPa) Data for Cu Substrate

S/N (Stress)	SAC105	SAC105-0.01GNS	SAC105-0.05GNS	SAC105-0.1GNS	SAC105-0.01CNT	SAC105-0.05CNT	SAC105-0.1CNT
1	8.87	13.21	9.82	9.15	10.98	9.08	5.38
2	4.91	9.19	5.57	10.66	9.47	12.53	3.71
3	10.77	10.23	8.47	4.50	5.18	11.38	10.47
4	3.01	12.17	4.22	6.01	6.69	7.93	8.80
Mean	6.89	11.2	7.02	7.58	8.08	10.23	7.09
Standard deviation	3.5567	1.8223	2.5746	2.8227	2.6258	2.0996	3.0928
Standard error	1.7783	0.9111	1.2873	1.4113	1.3129	1.0498	1.5464

Shear Force (N) Data for ENImAg Substrate

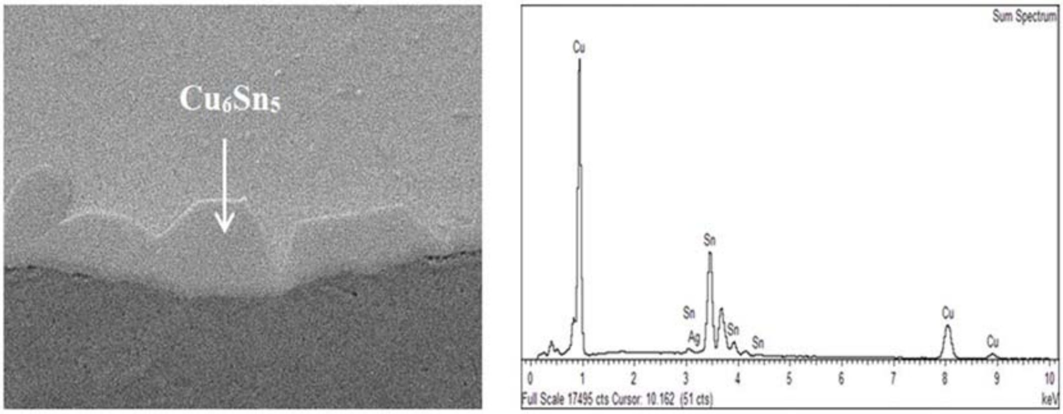
S/N (Force)	SAC105	SAC105-0.01GNS	SAC105-0.05GNS	SAC105-0.1GNS	SAC105-0.01CNT	SAC105-0.05CNT	SAC105-0.1CNT
1	1168.2	1433.3	1247.4	609.4	1166	1101.1	1256.2
2	973.5	1221	1017.5	751.3	1251.8	1293.6	1133
3	564.3	1392.6	946	1177	891	1331	877.8
4	368.5	1281.5	1175.9	1035.1	976.8	1175.9	754.6
Mean	768.9	1332.1	1096.7	893.2	1071.4	1225.4	1005.4
Standard deviation	366.74	97.988	139.007	259.072	166.32	105.996	229.757
Standard error	183.37	48.994	69.498	129.536	83.16	52.998	114.873

Shear Stress (MPa) Data for ENImAg Substrate

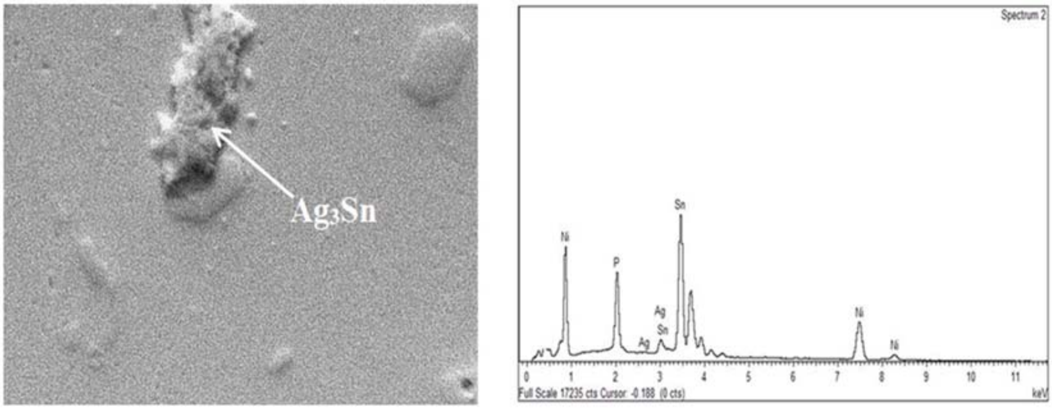
S/N (Stress)	SAC105	SAC105-0.01GNS	SAC105-0.05GNS	SAC105-0.1GNS	SAC105-0.01CNT	SAC105-0.05CNT	SAC105-0.1CNT
1	10.62	13.03	11.34	5.54	10.6	10.01	11.42
2	8.85	11.1	9.25	6.83	11.38	11.76	10.3
3	5.13	12.66	8.6	10.7	8.1	12.1	7.98
4	3.35	11.65	10.69	9.41	8.88	10.69	6.86
Mean	6.99	12.11	9.97	8.12	9.74	11.14	9.14
Standard deviation	3.334	0.8908	1.2637	2.3552	1.512	0.9636	2.0887
Standard error	1.667	0.4454	0.6318	1.1776	0.756	0.4818	1.0443

APPENDIX D

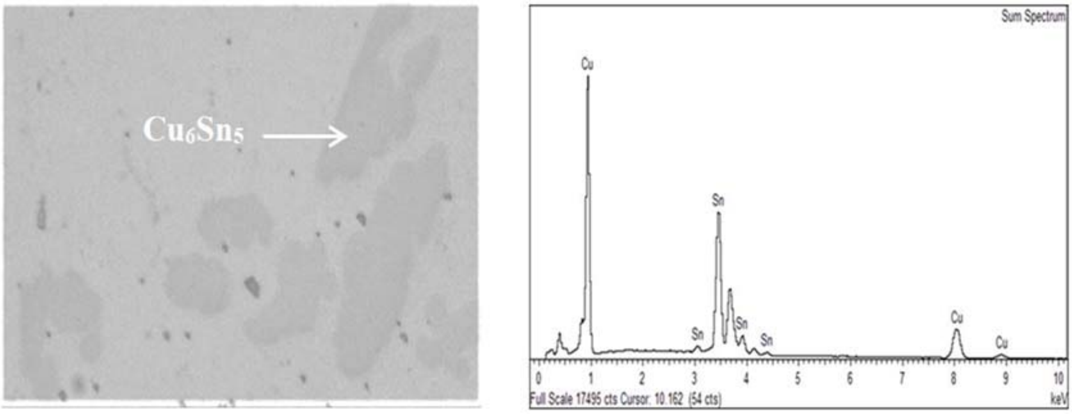
FESEM observation and EDX analysis for important solder compositions



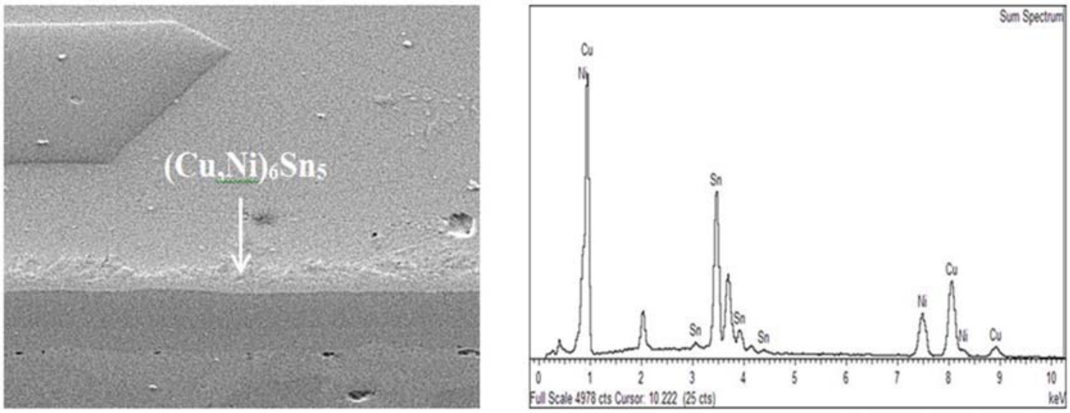
Cu_6Sn_5 interface in solder joint



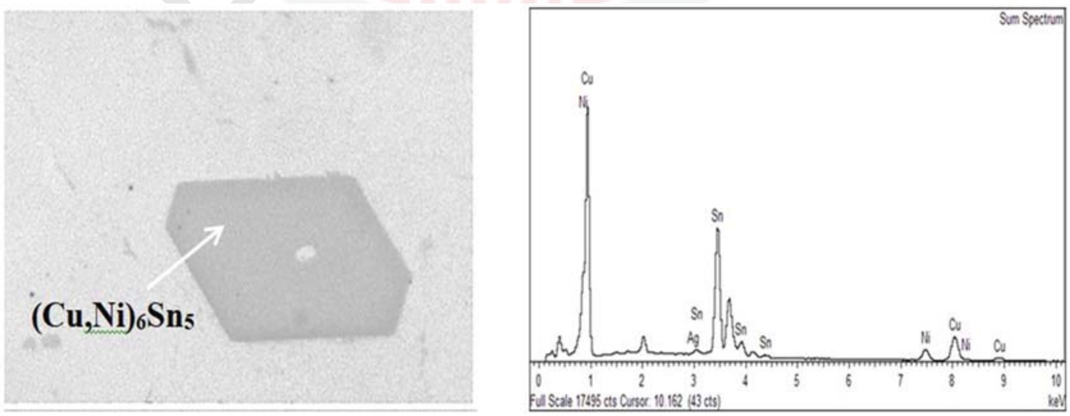
Ag_3Sn interface in solder joint



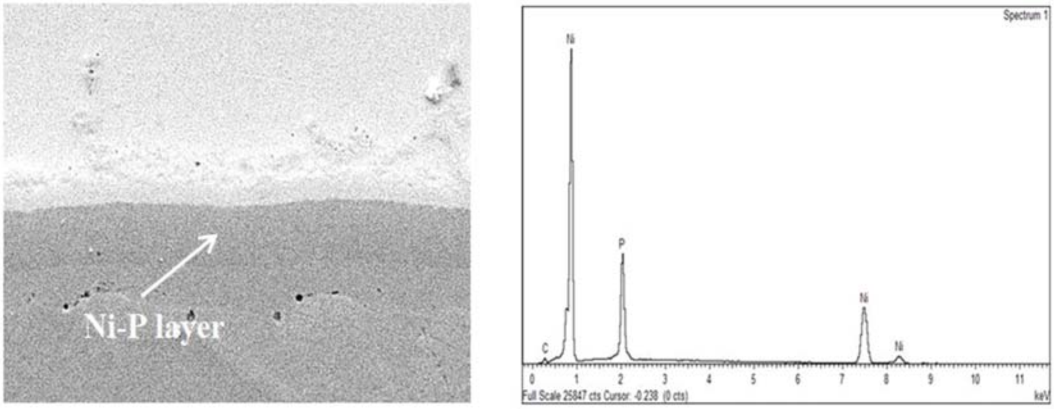
Cu_6Sn_5 IMC in solder matrix



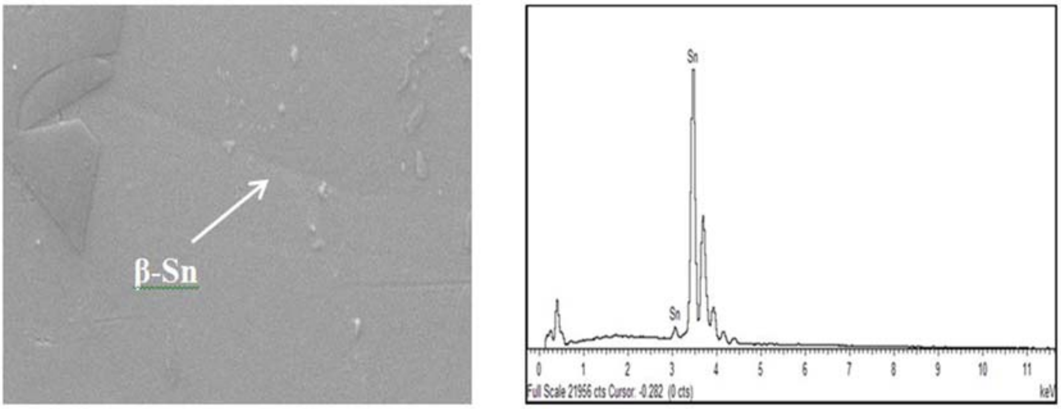
$(Cu,Ni)_6Sn_5$ interface in solder joint



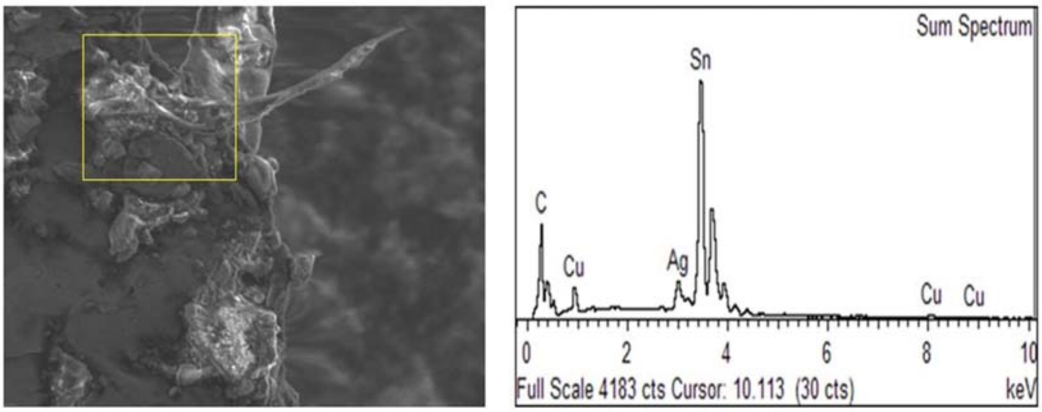
$(Cu,Ni)_6Sn_5$ IMC in solder matrix



Ni-P layer on ENImAg substrate



β-Sn phase in solder matrix



SAC105-0.05CNT/Cu fractured sample

BIODATA OF STUDENT

Vidyatharran s/o Krishna graduated from the Faculty of Mechanical Engineering at Universiti Malaysia Pahang, Pekan, Pahang in 2017 where accomplished with Bachelor of Science (Hons) in Mechanical Engineering. Currently pursuing as research student in Universiti Putra Malaysia (UPM) as Masters of Science (MSc) in Mechanical Engineering.

As a mechanical engineer, he has a strong background in the basic principles of engineering, methods and practices in mechanical system design, testing, and troubleshooting mechanical equipment. In addition, he is also proficient in using FEA software, advanced CAD designing tools and Stream Essential software.

His key strengths include effective communication, strong troubleshooting skills, as well as quick problem solving ability and most importantly, the passion to learn and adopt new technologies and skills. Years of education have molded him to be a go-getter that can excel and live up to the expectations in performing the duties assigned.

LIST OF PUBLICATIONS

Hanim, M. A., Dasan, A. B., Dele-Afolabi, T. T., Ariga, T., & Vidyatharran, K. (2021). Influence of porous Cu interlayer on the intermetallic compound layer and shear strength of MWCNT-reinforced SAC 305 composite solder joints. *Journal of Materials Science: Materials in Electronics*, *32*(4), 4515-4528.

K. Vidyatharran, M.A. Azmah Hanim, K.A. Matori and O. Saliza Azlina. Flood Detector System. Published e-book chapter for Symposium on Material Engineering and Applied Sciences 2019.

K. Vidyatharran, M.A. Azmah Hanim, K.A. Matori and O. Saliza Azlina. Growth of Interfacial Intermetallic Compounds between SAC305 with Cu Substrate in Different Cooling Rate. Published and Edited book chapter for Symposium and Workshop on Materials and Characterization 2018.