Sains Malaysiana 52(11)(2023): 3261-3272
http://doi.org/10.17576/jsm-2023-5211-18

Effect of Sn Plating Thickness on Wettability, Solderability, and Electrical Connections of Electronic Lead Connectors for Surface Mount Technology Applications

(Kesan Ketebalan Saduran Sn terhadap Kebolehbasahan, Kebolehpaterian dan Sambungan Elektrik bagi Kaki Penyambung Elektronik untuk Aplikasi Teknologi Lekapan Permukaan)

MARIA ABU BAKAR[1,*], MOHAMAD SOLEHIN MOHAMED SUNAR[1,2], AZMAN JALAR[1,3], A ATIQAH[1], FAKHROZI CHE ANI[2], IBRAHYM AHMAD[2] & ZOL EFFENDI ZOLKEFLI[2]

[1]*Institute of Microengineering and Nanoelectronics (IMEN), Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*
[2]*Western Digital®, SanDisk Storage Malaysia Sdn. Bhd. Plot 301A, Persiaran Cassia Selatan 1, Taman Perindustrian Batu Kawan, MK13, Batu Kawan, Seberang Perai Selatan, 14100, Penang, Malaysia*
[3]*Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*

Received: 1 August 2023/Accepted: 19 October 2023

ABSTRACT

The wettability of solder is important to achieve good solderability between the electronic component and printed circuit board (PCB). Tin (Sn) plating is widely used to promote the wettability of the solder on the substrates. However, an adequate amount of Sn plating thickness must be taken into consideration to acquire good wettability and solderability. Thus, this study investigates the Sn plating thickness of the electronic lead connector and their effect on the wettability and electrical connection. Two types of Sn plating thicknesses, ~3 µm, and 5 µm were applied on the electronic lead connector surface. It was found that the thin Sn plating thickness of ~3 µm has shown failure in electrical connections and lack of solder joint wettability and solderability properties. A thicker Sn plating thickness of 5 µm, has shown better wettability and solderability properties. In addition, the electrical connections also passed which implies that the thicker Sn plating thickness provides good solder joint establishment leading to good electrical connections. It is also observed that the better wettability of solder has been achieved for thicker Sn plating thickness. The finding from the field emission scanning electron microscope (FESEM) shows that the intermetallic compound (IMC) layer growth in the lead connector surface is regarded as abnormal for thin Sn plating thickness (~3 µm), in which the IMC layer was consumed and penetrating up to the surface of Sn-coating. This has led to poor solderability of the thin Sn plating with the solder to establish solder joint. The findings from this study have shed some light upon a better understanding of the importance of considering the adequate amount of Sn coating thickness to avoid IMC consumption at the Sn plating, better wettability properties, solderability, and solder joint quality for surface mount technology (SMT) especially for electronic lead connector applications.

Keywords: Electronic lead connector; IMC consumed at Sn plating; Sn plating thickness; solderability; surface mount technology; wettability

ABSTRAK

Kebolehbasahan pateri adalah penting untuk mencapai kebolehpaterian yang baik antara komponen elektronik dan papan litar bercetak (PCB). Saduran timah (Sn) digunakan secara meluas untuk menggalakkan kebolehbasahan pateri pada substrat. Walau bagaimanapun, ketebalan saduran Sn yang mencukupi harus diambil kira untuk memperoleh kebolehbasahan dan kebolehpaterian yang baik. Oleh itu, penyelidikan ini mengkaji ketebalan saduran Sn pada kaki penyambung elektronik dan kesannya terhadap kebolehbasahan dan sambungan elektrik. Dua jenis ketebalan saduran Sn, ~3 µm, dan 5 µm diaplikasikan pada permukaan kaki penyambung elektronik. Didapati bahawa saduran Sn yang nipis, ~3 μm telah menunjukkan kegagalan sambungan elektrik dan kekurangan dari segi sifat kebolehbasahan dan kebolehpaterian sambungan pateri. Saduran Sn yang tebal, 5 μm menunjukkan sifat kebolehbasahan dan kebolehpaterian yang lebih baik. Di samping itu, sambungan elektrik yang lulus menunjukkan bahawa ketebalan saduran Sn yang tebal menghasilkan sambungan pateri yang baik seterusnya memberikan sambungan elektrik yang baik. Turut diperhatikan bahawa kebolehbasahan pateri yang baik dicapai untuk saduran Sn yang tebal. Keputusan mikroskop elektron imbasan medan pancaran (FESEM) juga menunjukkan bahawa pertumbuhan lapisan sebatian antara logam (IMC) pada permukaan kaki penyambung dengan saduran Sn nipis (~3 μm) adalah tidak normal, yang mana lapisan IMC telah memakan dan menembusi ke permukaan saduran Sn. Ini mengakibatkan kebolehpaterian yang lemah antara pateri dan saduran Sn nipis untuk menghasilkan sambungan pateri. Penemuan daripada kajian ini telah memberikan pencerahan dan pemahaman yang lebih baik tentang kepentingan untuk mengambil kira ketebalan saduran Sn yang mencukupi bagi mengelakkan IMC memakan saduran Sn, sifat kebolehbasahan, kebolehpaterian dan kualiti sambungan pateri yang baik bagi teknologi lekapan permukaan (SMT) khususnya bagi aplikasi kaki penyambung elektronik.

Kata kunci: IMC memakan saduran Sn; kaki penyambung elektronik; kebolehbasahan; kebolehpaterian; ketebalan saduran Sn; teknologi lekapan permukaan

Introduction

Solder joint quality is important criteria for robust and reliable electrical and mechanical joining between two electronic components (Ismail, Bakar & Bakarudin 2020; Ismail et al. 2020; Ramli et al. 2020; Reddy et al. 2022). Wettability is one of the indicators of a good solder joint quality (Rahim et al. 2020). Solder joint wettability refers to the ability of molten solder to spread and wet the surface properly to form the solder joint. Lack of wettability can result in the formation of voids, gaps, or inadequate solder coverage (Khazaka et al. 2019; Soares et al. 2020; Yue et al. 2019). The voids degrade the mechanical strength of the solder joint, hence affecting its long-term reliability (Jia et al. 2023; Waseem et al. 2023). Insufficient wetting can also lead to low solder volume, which can result in insufficient electrical contact and poor heat conductivity (Ismail et al. 2022; Jayasekara et al. 2023; Jung & Jung 2019; Said et al. 2023).

To date, much research has been employed to improve the wettability of the solder joints such as surface cleaning of the substrate or components to be soldered (Curtulo et al. 2019; Podsiadły, Skalski & Słoma 2021; Ramli et al. 2019), addition of particles into solder alloy (Chen et al. 2023; Yuan et al. 2023), selection of the solder alloy as a solder material (Curtulo et al. 2019; Fazal et al. 2019; Ramli et al. 2019), flux application during the soldering process (Bušek et al. 2020; Gui et al. 2021; Veselý et al. 2020; Wang et al. 2021), temperature control during the soldering process (Akkara et al. 2020), modification of the substrate surface (Esfahani et al. 2020), including a pre-tinning application on the substrate (Dušek, Vávra & Rudajevová 2013; Hussein, Suryanarayana & Al-Aqeeli 2015; Liu et al. 2001; Zhao et al. 2022). Song et al. (2022) reported about the addition of appropriate amounts of nickel (Ni) and titanium dioxide (TiO_2) on the solder materials can refine the microstructure and improve the wettability.

The pre-tinning is one of the ways to improve the solder joint wettability. It is also known as tin plating (Sn plating), a process that involves the deposition of a layer of Sn on the substrate's surface. The Sn plating role is to provide a protective coating to prevent corrosion and most importantly to facilitate the soldering process. Huan et al. (2022) reported that the application of Sn plating with a thickness of 18 μm on the aluminum (Al) substrate has enhanced the wettability whereby the contact angle between the tin solder joint and the aluminum substrate is significantly decreased from 110° to 14°. The study on Sn plating more focused on different surface finishes on Sn plating solderability. By conducting a comparative study of Sn plating on various surface finishes for printed circuit boards (PCB), it was determined that certain surface finishes promoted better solder wetting with Sn plating (Atiqah et al. 2022). Moreover, another investigation was conducted to determine the influence of 1%-5% elemental lead (Pb) content in Sn plating on Sn whisker initiation and growth (Hillman et al. 2023). The acceptance and usage of pure tin by the electronics industry component fabricators are understandable as the pure Sn surface finishes are inexpensive, are simple plating systems to operate, and have reasonable solderability characteristics (Ashworth et al. 2015; Schetty 2001; Walsh & Low 2016). However, high-performance/harsh environment electronics typically have product life cycles that are measured in decades and therefore are much more susceptible to the potential long-term threat of Sn whiskers. The impact of aging on the solderability of Sn plating. By subjecting Ni and Sn-plated samples to accelerated aging tests for long-term reliability assessment, they found that small changes in intermetallic compound layer thickness and micromechanical properties were achieved using Ni coating as compared to Sn coating after subjected to the aging test for 1000 h (Afdzaluddin & Bakar, 2022).

Although Sn is plating on the surface of copper (Cu) as a protective layer, there is also the possibility of oxidation, which affects the wettability of tin plating, but the adequate amount of tin plating in terms of thickness is rarely reported. The objective of this study was to investigate the effects of Sn plating thickness on the wettability of the solder joint on the lead of the surface mount technology (SMT) connector to ensure good solderability for desired applications.

Materials and Methods

This work used a surface mount connector package consisting of six leads with a pitch size of 0.8 mm. The lead dimensions are 0.30 mm × 0.60 mm × 0.20 mm. The lead illustration is shown in Figure 1. The lead was made from copper zink (CuZn), then plated 1.30 µm Ni, gold (Au), and 3.0 µm Sn, respectively. The connector leads were mounted on the PCB using lead-free solder paste, Sn-Ag-Cu (SAC305). The thickness of PCB is 1.40 mm pad, and the surface finish of the Cu pad is organic solderability preservative (OSP). The SAC305 lead-free solder paste was printed into the PCB pads using a stencil printing process and the connector leads were attached to the PCB. Then, the reflow soldering process was carried out to establish the solder joint (BTU Pyramax 150N Z12) (Mohamed Sunar et al. 2022). The peak temperature range for the soldering process is between 235 °C and 260 °C. After the soldering process, the samples undergo the electrical test for functionality observation. From the preliminary results of the electrical test, it was found that all the samples have shown failed results on the electrical connection. The most possible reason for the failed electrical test is due to the non-establishment of the solder joint between the leads and PCB. In this case, this is probably due to the insufficient amount of Sn plating thickness on the lead tail that led to the non-establishment of the solder joint. This assumption is in line with the preliminary result on leads on the PCB (from X-ray laminography testing) that shows the leads have lifted over the PCB. This can be shown by the lower brightness observed for the failed leads. After taking a closer look at the materials involved and the soldering process, the Sn coating is one of the possible factors that are responsible to facilitate good joining based on the existing structure of the connector lead. Thus, this becomes our motivation to investigate further the Sn plating thickness whereby the preliminary investigation used a Sn plating thickness of ~3.0 µm.

Hence, this work was conducted by using two types of Sn plating thickness, 3.0 µm, and 5.0 µm whereas all the other parameters such as SMT connector material, lead, PCB, solder paste, and the soldering process were fixed. For each Sn plating thickness, a total of six leads were used for each testing and characterization. After the Sn plating process, metallographic techniques were carried out to prepare a cross-section of the samples. The samples were cut using the laser cutting method (3801 Series Fibercube Laser Marking and Engraving System) through a section that was perpendicular to the lead solder tail, the area of the solder joint connected

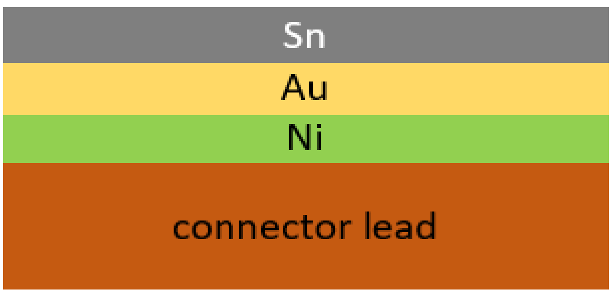

FIGURE 1. Illustration of connector lead with its plating materials

between the lead and the PCB (Figure 2). Then, the samples were put into the silicon rubber molds. Next, the samples were cold mounted using a mixture of hardener (speciFix-40 curing agent) and resin (speciFix) and left to be hardened for about 24 h (Figure 3). After the samples were hardened, the samples were taken out from the silicon rubber molds, and the grinding process was performed using silicon carbide (SiC) abrasive paper of 240, 320, 600, 800, 1000, and 2000 grit sizes (Yusoff, Bakar & Jalar 2022). Subsequently, polishing was conducted using 3 µm diamond paste suspension followed by 0.3 µm and 0.04 µm of oxide polishing suspension (OP-S) for 30-60 s. The samples were then characterized using a field emission scanning electron microscope (FESEM - Hitachi SU3500) equipped with element dispersive energy (EDX) to capture the microstructure and detect the existence of elements at the solder joint. The thicknesses of the Sn plating at the leads were measured accordingly.

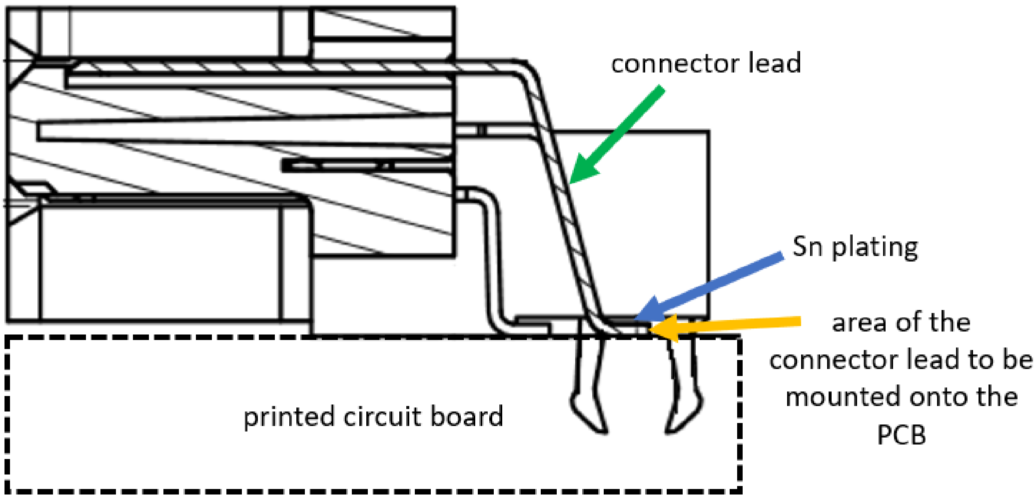

FIGURE 2. Schematic side view location of the connector lead, Sn plating, and the area of the connector lead to be mounted to the PCB

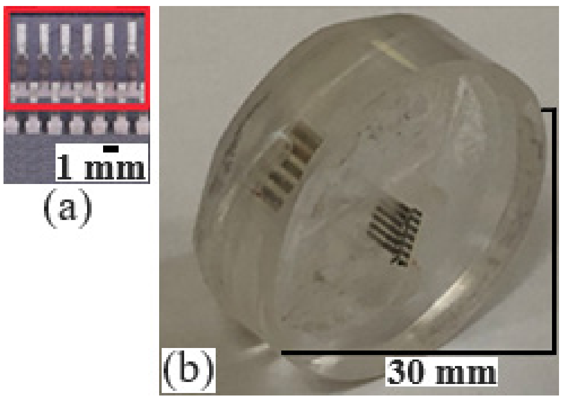

FIGURE 3. (a) Leads of SMT connector and (b) leads in hardened cold-mounted resin epoxy

For the solderability test, another sample after the Sn plating process underwent the dip and look test according to standard K-STD-002E. The solder bath of SAC305 alloy condition is maintained at 255 °C during the solderability test. The flux for the lead-free solderability test is a standard activated rosin flux containing 25 wt.% colophony and 0.39 wt.% diethyl ammonium hydrochloride in 74.61 wt.% isopropyl alcohol with a dwell time of 5 s without pre-heating. The leads were submerged with a dipping angle of 90° individually into the molten solder and discarded after dwell time was achieved (Figure 4). The solder spread coverage area was captured and calculated using an optical microscope (Keyence Scope VH-Z50T).

Subsequently, another batch of leads was taken for joining on the PCB, a similar process as the preliminary experiment above. The SAC305 solder paste was printed on the PCB and used to attach the leads to the PCB. To establish the joining between the leads and PCB, a reflow soldering was carried out. After the establishment of the joining, all the samples were examined via X-ray laminography (OMRON VT-X750). This testing is used to capture the images of the solder joint area and geometries (shape). The capabilities of the testing are for detecting the existence of voids, bridging, misalignment, and gross solder joint opens. After undergoing the X-ray laminography test, the electrical testing (MPT3K Advantest) was performed using the same samples. The electrical test was implemented for the detection of failure related to the signal transmitted i.e., the detection of solder joint defect. The test duration is 18 h, and the component voltage input is 12V under 25 °C. The purpose of the electrical testing is to ensure good functionality of the component. The electrical test machine only detects whether the component has passed or failed the functionality test by giving output ‘pass’ or ‘fail’. Figure 5 shows the diagram of the electrical test for six leads (leads are labeled as 1, 2, 3, 4, 5, and 6). Figure 5 is an example of a lead function whereby the 3 leads will not give an impact to the test component. 1 and 2 are reference clocks that are bypassed with 0-ohm Resistors. Label 6 in the schematic diagram shows that there is no connection. The command set of this testing could not be able to send a signal to the component if there are solder joint issues detected at 3, 4, and 5. Therefore, the component could not function, and this indicates that the electrical functionality failed.

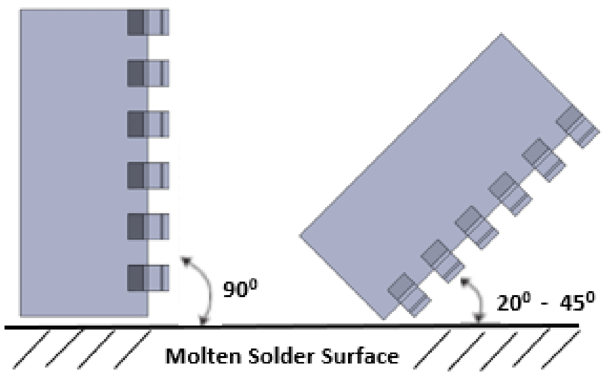

FIGURE 4. Schematic of solderability testing: The solder dipping angle of the leads into the molten solder

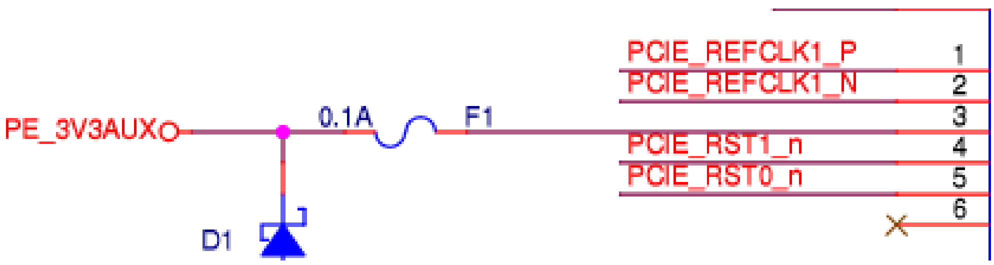

FIGURE 5. Electrical test diagram for six leads

Results and Discussion

Preliminary result of the electrical test for the solder joint between lead with Sn plating of ~3.0 µm and PCB has shown that all the solder joints have failed in the electrical testing. Figure 6 shows the X-ray laminography image of six leads. The result shows that three out of six leads are failed (bad condition) whereby another three pass the electrical test. By taking a closer look at the results, it is shown that the bigger coverage image of the leads indicates that the leads are not connected to the PCB while the less coverage indicates that the leads are having an established joining to the PCB. The results show that the joining between the leads and the PCB are inconsistent whereby some of the solder joint have good quality and some of its having lack of solder joint quality. Due to the unestablished joining between the leads and the PCB which leads to the failed electrical connection, therefore, the overall performance of this SMT connector component failed to function properly. Thus, future analysis of this study is to investigate the establishment of solder joint whereby the Sn plating thickness on the lead becomes variable in this study to be further analyzed.

Figure 7(a) shows the micrograph of cross-section lead with Sn plating of ~3 µm thickness using FESEM while Figure 7(b) is for thicker Sn plating of ~5 µm. The intermetallic compound layer also formed at the interface between the Ni layer and the Sn plating layer which shows the establishment of the Sn plating layer on

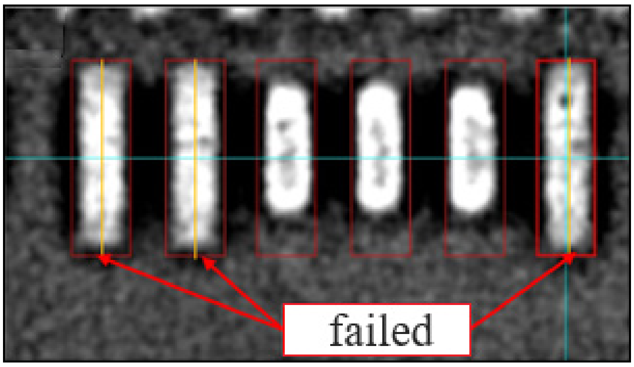

FIGURE 6. X-ray laminography image of six leads connected to the PCB

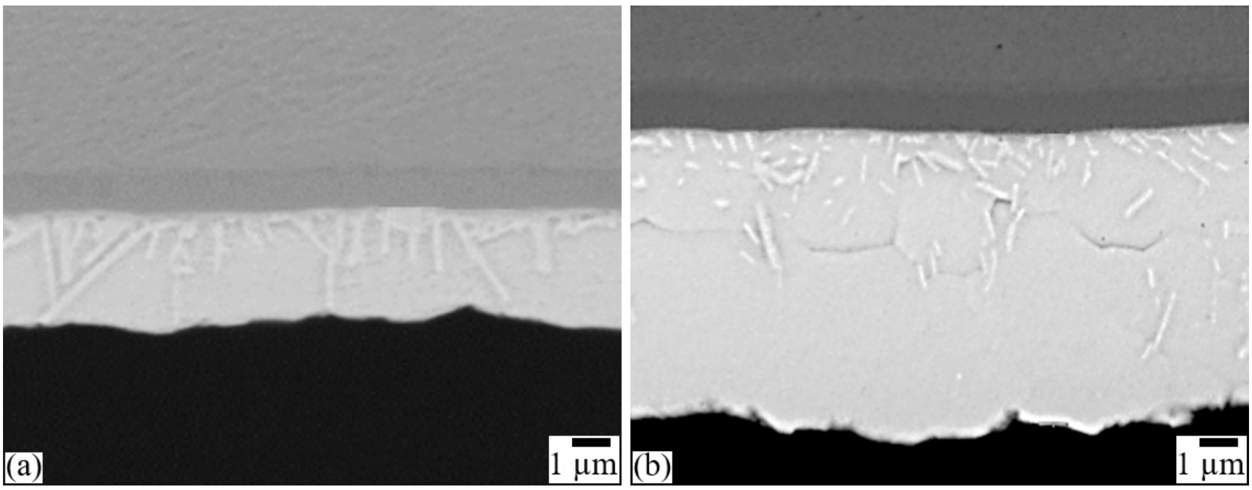

FIGURE 7. Micrograph of cross-section leads with Sn plating thickness of: (a) ~3 µm and (b) ~5 µm

top of the Ni layer. The average Sn plating was measured using FESEM. The thickness of the Sn plating of ~3 µm and ~5 µm are approximately ranged from 2.51-3.05 µm and 5.48-7.49 µm, respectively. Figure 8 shows the element of Sn, carbon (C), and Ni which formed for the IMC layer at the lead surface, in which the IMC needle-like has protruded through the Sn plating from the Ni plating interface. It has been known that the formation of certain IMC layers in Sn-based plating can have an undesirable effect resulting in a serious degrading of component solderability. This happens when the IMC penetrates through the Sn layer to the surface and as a result, the Sn layer becomes thinner. This significantly affects the solderability between the Sn layer and the solder materials whereby adequate Sn layer thickness plays a role in providing good metallurgical solder joint. However, it is noticed that for the lead with Sn plating of ~5 µm sample, most of the IMC does not protrude up from the lead surface. This indicates that an adequate Sn layer amount of above 5 µm could give a lower risk of solderability degradation whereby the IMC formation does not consume all the Sn layer on the lead.

Figure 9 shows a boxplot of the Sn plating thickness used in this study. The Sn plating thicknesses were

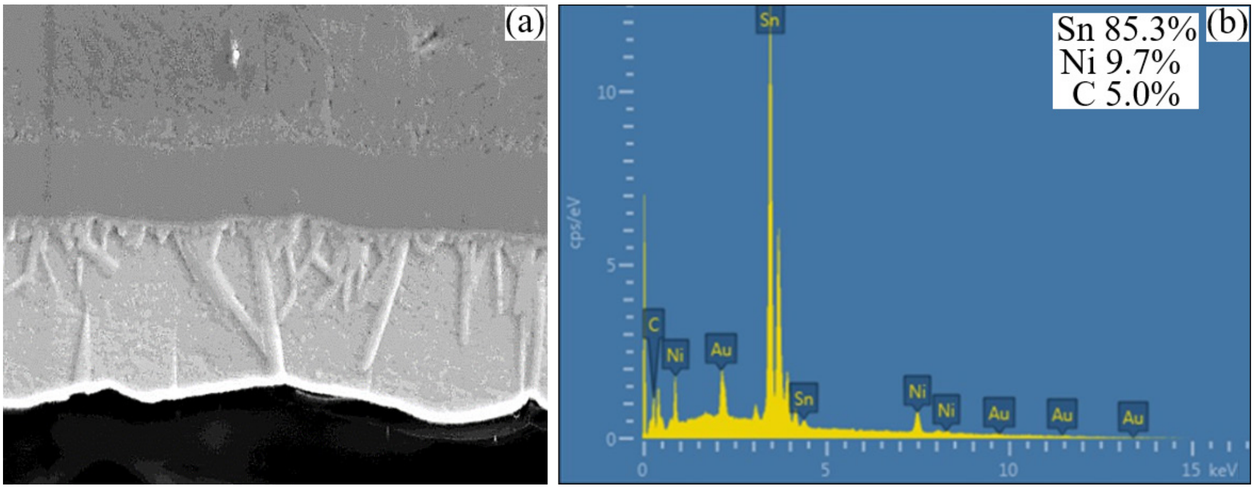

FIGURE 8. (a) Micrograph of cross-section lead with Sn plating of ~3 µm thickness and (b) EDX spectrum at the point located at the IMC layer in the red box of (a)

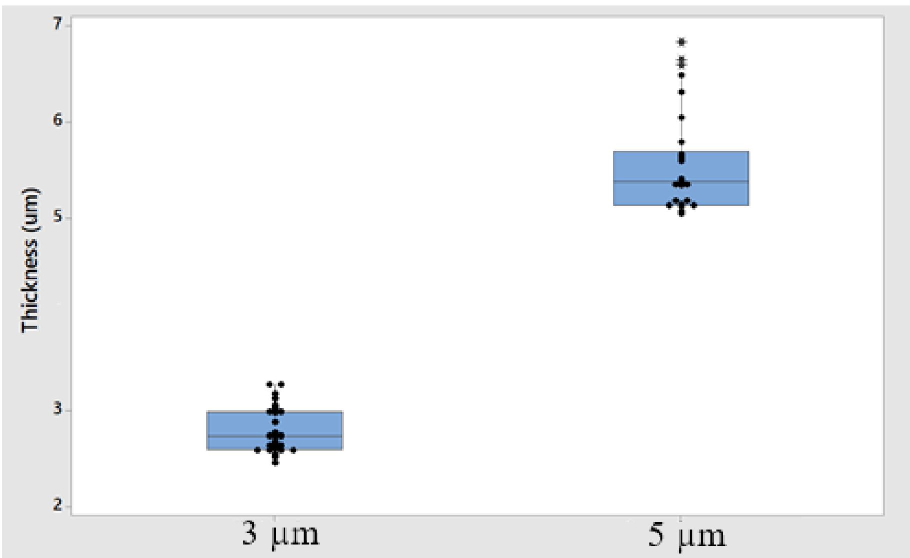

FIGURE 9. Boxplot of Sn plating thickness

measured by FESEM. For samples of Sn plating ~3 µm shows the lower range of values is 2.43 µm. Meanwhile, for samples of Sn plating 5 µm shows the lower range of values is 5.04 µm. The consistency of Sn plating is ~3 µm as compared to Sn plating 5 µm. This is due to the aim of this work was to observe the role of thin and thick Sn plating thickness whereby the minimum thickness for the thick Sn layer thickness is more than 5 µm. Some works have also applied the Sn plating to induce good wettability of the solder joint with a thickness of 18 µm (Huan et al. 2022).

Figure 10 shows the wettability on the leads with two type of Sn plating, ~3 µm and 5 µm from dip and look testing. It is noticeable that the wettability is within the range of 10-50% only as shown in Figure 10(a)-10(f). Meanwhile, the solder joint wettability on the leads with Sn plating 5 µm has shown 100% as shown in Figure 10(g)-10(l). This can be recognized by the smooth appearance of the solder joint with Sn plating of 5 µm in Figure 10(g)-10(l) as compared to solder joint with Sn plating of ~3 µm in Figure 10(a)-10(f)).

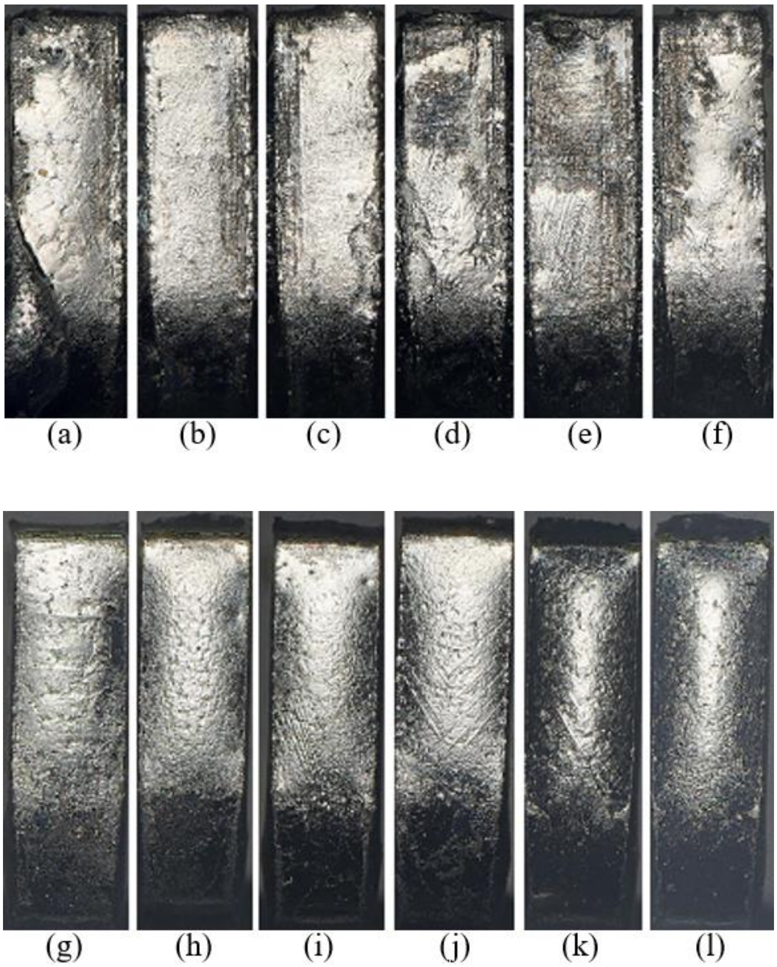

FIGURE 10. Solder joint wettability of the leads for Sn plating ~3 µm: (a) 40%, (b) 20%, (c) 10% (50%), (d) 50%, (e) 40%, (f) 40% and for Sn plating 5 µm: (g) 100% (h) 100% (i) 100% (j) 100% (k) 100% and (l) 100%

The finding indicates that good wettability has been achieved for these samples. The desired solder joint wettability is 100% whereby it can give good contact between the component and substrate leading to an adequate current flow for the electrical connection. The improvement in solder wettability which contributes to good solderability is significantly contributed by the amount of Sn plating thickness. An adequate and suitable amount of Sn plating in terms of thickness has provided lower surface tension, thus leading to better wettability and solderability of the solder joint between the Sn surface and PCB. The formation of the Cu-Sn phase by the interaction of Sn and Cu at the interface, leading to a decrease in surface tension and a release of free energy on the occasion of wetting and spreading, may be attributed to better spreading (Liu et al. 2001). The results show that a thicker Sn plating thickness of 5 μm provides better solderability for the solder materials to form solder joints. It is known that the Ni layer is used as a barrier to suppress the IMC layer growth and the Au layer is used to protect the Ni layer from oxidation. Therefore, the Sn plating is used to promote the wettability by utilizing the Au is dissolve during the solidification and soldering process. For this case, suitable Sn plating layer thickness is critical as an adequate amount of the Sn plating will ensure the Au will dissolve properly during the solidification and soldering process.

The effect of Sn coating thickness is further investigated on the electrical connectivity through electrical testing and X-ray laminography for the establishment of solder joints between the leads and PCB. Figure 11 shows that lead with Sn plating 5 μm has a good solder joint establishment and this is in line with the finding on the solder wettability via the dip and look test. Good solder spreads and good solderability was achieved for lead with Sn plating of 5 μm. The electrical results show a passed result for all leads with Sn plating of 5 μm, meanwhile, the electrical connection for the lead with Sn plating ~3 μm has shown failed results. This indicates that the establishment of solder joints provides good current flow for the electrical connections. Therefore, the component can function very well. Figure 12 shows the cross-section micrograph of the solder joint with Sn plating of ~3 μm and 5 μm, respectively. Lead with Sn plating of ~3 μm does not form any solder joint between the lead and PCB due to non-wetting between the Sn plating layer with the solder materials. By taking a closer look at Figure 12 (b), the inset (Figure 12 c) shows that the IMC has consumed the Sn plating layer and subsequently, the Sn plating layer become very thin and not adequate to promote good solderability between the Sn plating layer and solder materials. Thus, this contributes to non-wetting and non-establishment of solder joints.

FIGURE 11. X-ray laminography of lead with Sn plating 5 μm

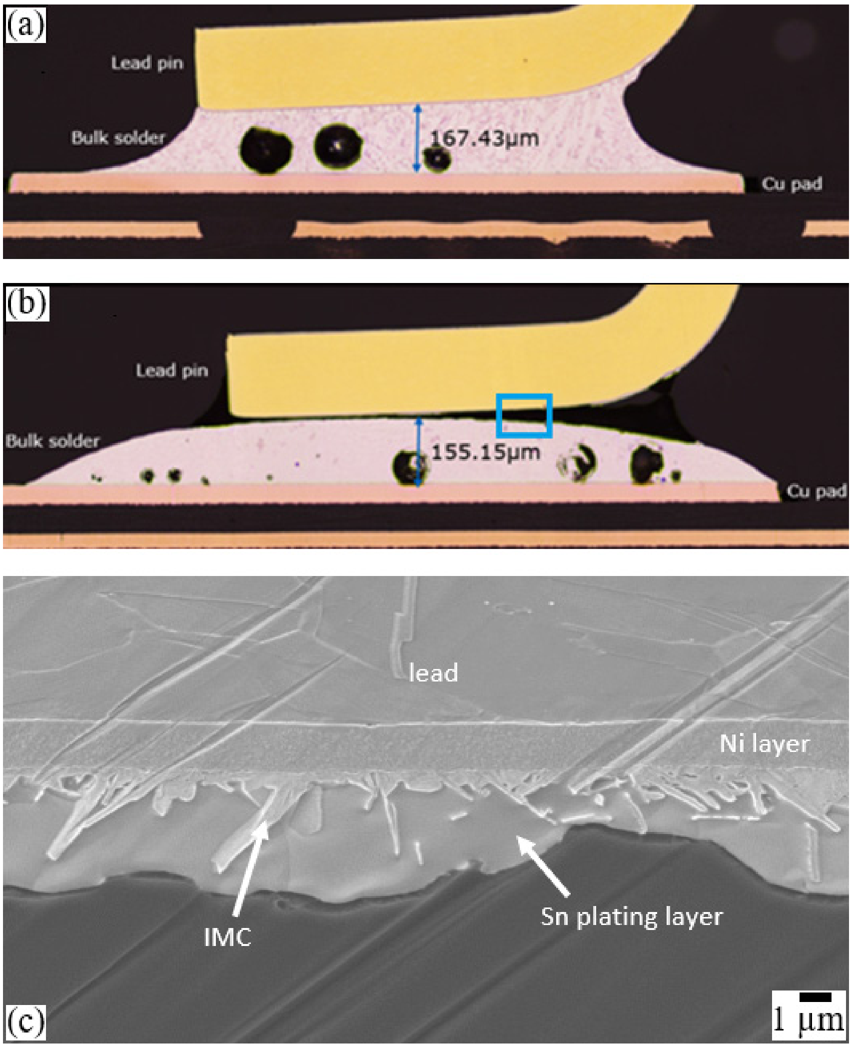

FIGURE 12. Micrograph of the cross-section for (a) established solder joint between lead and solder with Sn plating 5 µm, (b) non-wetting and non-established solder joint between lead with Sn plating 3 µm and solder, (c) inset of (b) non-wetting due to IMC consumed at the Sn layer at lead area

Conclusions

This study has successfully investigated the Sn plating thickness of the leads for SMT connectors. A preliminary study has shown the thin Sn plating thickness of ~3.0 µm has shown the electrical connection failure due to the lack of wetting between the lead and solder, leading to the non-establishment of solder joint between the leads and the PCB. Further analysis of the effect of Sn plating thickness has shown that the amount of Sn coating thickness plays an important role in providing good solder-wetting quality. The findings show that the Sn plating thickness of ~3.0 µm is not adequate for good solder wetting quality whereby the IMC has consumed the Sn plating layer and prevented wetting between the Sn plating layer and the solder material leading to poor solderability. The findings of this study have shown that the Sn coating of 5.0 µm provides 100% solder wetting, the establishment of the solder joint, and the component involved passed the electrical testing. In summary, this study shows that adequate Sn plating thickness must be considered to avoid IMC consumption, better wettability, good solderability, and reliable solder joint quality.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support provided by Western Digital via SanDisk Storage Malaysia Sdn. Bhd through research grant (RR-2020-004) and collaboration activities with Universiti Kebangsaan Malaysia. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Azman Jalar reports financial support was provided by Western Digital Malaysia. Azman Jalar reports a relationship with Western Digital Malaysia that includes funding grants.

REFERENCES

Afdzaluddin, A.M. & Bakar, M.A. 2020. Effect of coating element on joining stability of Sn-0.3 Ag-0.7 Cu solder joint due to aging test. *Sains Malaysiana* 49(12): 2983-2990.

Akkara, F.J., Abueed, M., Belhadi, M., Wei, X., Hamasha, S., Ali, H., Suhling, J. & Lall, P. 2020. Reliability of new SAC-Bi solder alloys in thermal cycling with aging. *Proc. IPC APEX* pp. 1-8.

Ashworth, M.A., Wilcox, G.D., Higginson, R.L., Heathm R.J., Liu, C. & Mortimer, R.J. 2015. The effect of electroplating parameters and substrate material on tin whisker formation. *Microelectronics Reliability* 55: 180-191.

Atiqah, A., Jalar, A., Bakar, M.A. & Ismail, N. 2022. Advancement of Printed Circuit Board (PCB) surface finishes in controlling the Intermetallic Compound (IMC) growth in solder joints, In *Recent Progress in Lead-Free Solder Technology. Topics in Mining, Metallurgy and Materials Engineering*, edited by Salleh, M.A.A.M., Abdul Aziz, M.S., Jalar, A. & Izwan Ramli, M.I. Springer, Cham. pp. 217-238.

Chen, C., Zhang, L., Wang, X., Lu, X. & Guo, Y.H. 2023. Microstructure and properties of Sn58Bi/Ni solder joint modified by Mg particles. *Journal of Materials Research and Technology* 24: 514-526.

Curtulo, J.P., Dias, M., Bertelli, F., Silva, B.L., Spinelli, J.E., Garcia, A. & Cheung, N. 2019. The application of an analytical model to solve an inverse heat conduction problem: Transient solidification of a Sn-Sb peritectic solder alloy on distinct substrates. *Journal of Manufacturing Processes* 48: 164-173.

Dušek, K., Vávra, J. & Rudajevová, A. 2013. Effect of reflow technology and surface finishes of PCB on solder spreading. *Proc. 36th Int. Spring Semin. Electron. Technol., IEEE.* pp. 136-139.

Esfahani, R.N., Shuttleworth, M.P., Doychinov, V., Wilkinson, N.J., Hinton, J., Jones, T.D.A., Ryspayeva, A., Robertson, I.D., Marques-Hueso, J. & Desmulliez, M.P.Y. 2020. Light based synthesis of metallic nanoparticles on surface-modified 3D printed substrates for high performance electronic systems. *Additive Manufacturing* 34: 101367.

Fazal, M.A., Liyana, N.K., Rubaiee, S. & Anas, A. 2019. A critical review on performance, microstructure and corrosion resistance of Pb-free solders. *Measurement* 134: 897-907.

Gui, Z., Hu, X., Jiang, X., Li, Y. & Wang, H. 2021. Interfacial reaction, wettability, and shear strength of ultrasonic-assisted lead-free solder joints prepared using Cu–GNSs-doped flux. *Journal of Materials Science: Materials in Electronics* 32: 24507-24523.

Hillman, D., Pearson, T., Wilcoxon, R., Cooke, G., Margheim, S., Gladen, E., Munson, T. & Fritz, D. 2023. The Influence of element lead (Pb) content in tin plating on tin whisker initiation/growth. *Journal of Surface Mount Technology* 36: 2-11.

Huan, P-C., Tang, X-X., Sun, Q., Akira, K., Wang, X-N., Wang, J., Wang, J-L., Wei, X. & Di, H-S. Comparative study of solder wettability on aluminum substrate and microstructure-properties of Cu-based component/aluminum laser soldering joint. *Materials & Design* 215: 110485.

Hussein, M.A., Suryanarayana, C. & Al-Aqeeli, N. 2015. Fabrication of nano-grained Ti–Nb–Zr biomaterials using spark plasma sintering. *Materials & Design* 87: 693-700.

Ismail, N., Atiqah, A., Jalar, A., Bakar, M.A., Rahim, R.A.A., Ismail, A.G., Hamzah, A.A. & Keng, L.K. 2022. A systematic literature review: The effects of surface roughness on the wettability and formation of intermetallic compound layers in lead-free solder joints. *Journal of Manufacturing Processes* 83: 68-85.

Ismail, N., Bakar, M.A. & Bakarudin, S.B. 2020. Effect of temperature on strain-induced hardness of lead-free solder wire using nanoindentation approach. *Sains Malaysiana* 49(12): 3073-3080.

Ismail, N., Jalar, A., Yusoff, W.Y.W., Safee, N.S. & Ismail, A. 2020. Effect of shock wave on constant load behaviour of Pb-Free/CNT solder joint. *Sains Malaysiana* 49(12): 3037-3044.

Jayasekara, H., Zhang, Q., Yuen, C., Zhang, M., Woo, C.W. & Low, J. 2023. Detecting anomalous solder joints in multi-sliced PCB X-ray images: A deep learning based approach. *SN Computer Science* 4: 307.

Jia, F., Niu, L., Xi, Y., Qiu, Y., Ma, H. & Yang, C. 2023. Experimental and multiphysics simulation study of atoms migration and morphology evolution in solder joints under high current density. *International Journal of Heat and Mass Transfer* 202: 123719.

Jung, D-H. & Jung, J-P. 2019. Review of the wettability of solder with a wetting balance test for recent advanced microelectronic packaging. *Critical Reviews in Solid State and Materials Sciences* 44: 324-343.

Khazaka, R., Martineau, D., Youssef, T., Le, T.L. & Azzopardi, S. 2019. Rapid and localized soldering using reactive films for electronic applications. *Journal of Microelectronics and Electronic Packaging* 16: 182-187.

Liu, C.Y., Li, J., Vandentop, G.J., Choi, W.J. & Tu, K-N. 2001. Wetting reaction of Sn-Ag based solder systems on Cu substrates plated with Au and/or Pd layer. *Journal of Electronic Materials* 30: 521-525.

Mohamed Sunar, M.S., Abu Bakar, M., Jalar, A., Ramli, M.R. & Che Ani, F. 2022. Effect of alloy particle size and stencil aperture shape on solder printing quality. *Microelectronics International* 39(2): 81-90.

Podsiadły, B., Skalski, A. & Słoma, M. 2021. Soldering of electronics components on 3D-printed conductive substrates. *Materials (Basel)* 14: 3850.

Rahim, R.A.A.A., Zulkifli, M.N., Jalar, A., Afdzaluddin, A.M. & Shyong, K.S. 2020. Effect of isothermal aging and copper substrate roughness on the SAC305 solder joint intermetallic layer growth of high temperature storage (HTS). *Sains Malaysiana* 49(12): 3045-3054.

Ramli, M.I.I., Mohd Salleh, M.A.A., Amli, S.F.M. & Razak, N.R.A. 2020. Effect of bismuth additions on wettability, intermetallic compound, and microhardness properties of Sn-0.7 Cu on different surface finish substrates. *Sains Malaysiana* 49(12): 3201-3205.

Ramli, M.I.I., Mohd Salleh, M.A.A., Mohd Sobri, F.A., Narayanan, P., Sweatman, K. & Nogita, K. 2019. Relationship between free solder thickness to the solderability of Sn–0.7 Cu–0.05 Ni solder coating during soldering. *Journal of Materials Science: Materials in Electronics* 30: 3669-3677.

Reddy, V.V.B., Gupta, S., Williamson, J. & Sitaraman, S.K. 2022. Correlation studies between laser ultrasonic inspection data and finite-element modeling results in evaluation of solder joint quality in microelectronic packages. *Journal of Electronic Packaging* 144: 11009.

Said, M., Salleh, N.A., Nazeri, M.F.M., Akbulut, H., Kheawhom, S. & Mohamad, A.A. 2023. Microwave hybrid heating for lead-free solder: A review. *Journal of Materials Research and Technology* 26: 6220-6243.

Schetty, R. 2001. Minimization of tin whisker formation for lead-free electronics finishing. *Circuit World* 27: 17-20.

Soares, T., Cruz, C., Silva, B., Brito, C., Garcia, A., Spinelli, J.E. & Cheung, N. 2020. Interplay of wettability, interfacial reaction and interfacial thermal conductance in Sn-0.7 Cu solder alloy/substrate couples. *Journal of Electronic Materials* 49: 173-187.

Song, Q., Li, Y., Yu, J., Qi, D., Qin, W. & Zhan, Y. 2022. Effect of Ni and TiO2 particle addition on the wettability and interfacial reaction of Sn20Bi lead-free solder. *Journal of Materials Science: Materials in Electronics* 33: 3306-3319.

Veselý, P., Bušek, D., Krammer, O. & Dušek, K. 2020. Analysis of no-clean flux spatter during the soldering process. *Journal of Materials Processing Technology* 275: 116289.

Walsh, F.C. & Low, C.T.J. 2016. A review of developments in the electrodeposition of tin. *Surface and Coatings Technology* 288: 79-94.

Wang, H., Hu, X., Jiang, X. & Li, Y. 2021. Interfacial reaction and shear strength of ultrasonically-assisted Sn-Ag-Cu solder joint using composite flux. *Journal of Manufacturing Processes* 62: 291-301.

Waseem, A., Ibrahim, M.S., Lu, C., Waseem, M., Lee, H.H. & Loo, K.H. 2023. The effect of pre-existing voids on solder reliability at different thermomechanical stress levels: Experimental assessment. *Materials & Design* 233: 112275.

Yuan, P., Chen, D., Qin, J., Bai, H., Zhang, X., Gan, G., Leng, C. & Yan, J. 2023. Effects of Ag3Sn nanoparticles and isothermal aging on IMC layer growth, mechanical properties, and life prediction of SAC305/Cu solder joints. *Composites and Advanced Materials* 32.

Yue, W., Zhang, J-X., Gong, C-G., Zhou, M-B. & Zhang, X-P. 2019. Identification of essential factors causing solder bridging of right-angle solder interconnects in laser jet solder ball bonding process. *20th International Conference on Electronic Packaging IEEE.* pp. 1-4.

Yusoff, F.A.M., Bakar, M.A. & Jalar, A. 2022. Kesan rawatan termomekanik dengan mampatan tunggal terhadap mikrostruktur dan sifat mikromekanik aloi pateri Sn-0.7Cu. *Sains Malaysiana* 51(11): 3775-3784.

Zhao, P.J., Chen, Z.H. & Dong, C.F. 2014. Failure analysis of warm stamping of magnesium alloy sheet based on an anisotropic damage model. *Journal of Materials Engineering and Performance* 23: 4032-4041.

Zhao, S., Tan, Z., Wang, H. & Gao, M. 2022. Effects of spreading behaviors on dynamic reflectivity in laser soldering. *Optics & Laser Technology* 155: 108404.

*Corresponding author; email: maria@ukm.edu.my