

CORRELATION BETWEEN SURFACE PROFILE PARAMETERS AND WETTING DYNAMICS OF SN-CU SOLDER ON MODIFIED COPPER SUBSTRATES

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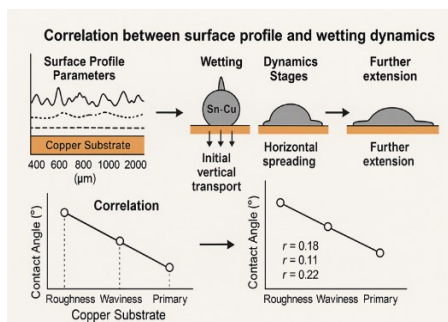
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Graphical abstract



Abstract

In the previous research, selection of substrate surface profile to optimize wetting is a problem. There is lack of quantitative data on the wetting dynamics of Sn-Cu solder on copper substrates. This study investigates the correlation between surface profile parameters and wetting dynamics of Sn-Cu solder on modified copper substrates. In the past up till the present, this study profound solution by varying substrate surface profile using roughness, waviness, and primary profile parameters within the ranges from 400, 600, 800, 1000, 1200, and 2000 μm. Excellent wetting angle of contact (18.58°, 32.02°, 22.73°, 23.26°, 26.05°, and 25.93°) were recorded which agreed with the literature of the ranging values > 0 and < 90°. These findings indicate that the wetting dynamics of Sn-Cu solder on modified copper substrates gives an optimal spreading on copper substrate surface. This is characterized by three distinct stages: initial vertical transport of molten solder, horizontal spreading within the droplet's spherical diameter, and further horizontal extension influenced by modified copper substrates. A correlation equation was established between surface profile parameters and wetting dynamics of Sn-Cu solder with correlation coefficients of $r = 0.18$ (roughness), $r = 0.11$ (waviness), and $r = 0.22$ (primary), indicating that substrate surface profiles correlate with dynamics wetting angles with substrate surface profile (primary) most influences wettability. This work will bring an improvement in printed circuit board etching or soldering efficiency and metallurgical joining.

Keywords: Sn-Cu solder, wetting dynamics, surface profile parameters, copper substrate, surface roughness, waviness, primary

Abstrak

Dalam kajian terdahulu, pemilihan profil permukaan substrat untuk mengoptimalkan kebasahan merupakan satu masalah. Terdapat kekurangan data kuantitatif mengenai dinamik kebasahan pateri Sn-Cu pada substrat kuprum. Kajian ini mengkaji hubungan antara parameter profil permukaan dan dinamik kebasahan pateri Sn-Cu pada substrat kuprum yang diubah suai. Dari dahulu hingga kini, kajian ini menawarkan penyelesaian yang bermakna dengan mempelbagaikan profil permukaan substrat menggunakan parameter kekasaran, gelombang, dan profil primer dalam julat 400, 600, 800, 1000, 1200, dan 2000 μm. Sudut sentuhan kebasahan yang sangat baik direkodkan (18.58°, 32.02°, 22.73°, 23.26°, 26.05°, dan 25.93°) yang bersetuju dengan julat nilai dalam

literatur iaitu lebih daripada 0 dan kurang daripada 90°. Penemuan ini menunjukkan bahawa dinamik kebasahan pateri Sn-Cu pada substrat kuprum yang diubah suai menghasilkan penyebaran optimum di permukaan substrat kuprum. Ini dicirikan oleh tiga peringkat yang berbeza: pengangkutan menegak awal pateri cair, penyebaran mendatar dalam diameter sfera titisan, dan lanjutan mendatar selanjutnya yang dipengaruhi oleh substrat kuprum yang diubah suai. Satu persamaan korelasi telah ditetapkan antara parameter profil permukaan dan dinamik kebasahan pateri Sn-Cu dengan pekali korelasi $r = 0.18$ (kekasaran), $r = 0.11$ (gelombang), dan $r = 0.22$ (primer), menunjukkan bahawa profil permukaan substrat berkorelasi dengan sudut kebasahan dinamik, di mana profil permukaan (primer) paling mempengaruhi kebolehebasan. Kajian ini dijangka dapat meningkatkan kecekapan etsa papan litar bercetak atau pematerian serta penyambungan metalurgi.

Kata kunci: Pateri Sn-Cu, dinamik pembasahan, parameter profil permukaan, substrat kuprum, kekasaran permukaan, gelombang permukaan, primer

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1.0 INTRODUCTION

Solderability of a substrate is a measure of the ease by which it can be joined with a solder melt or the liquid solder to form a permanent solder joint [1]. It depends on the composition of the solder, the force of gravity by which the solder liquid takes from an appreciable height distance to meet a substrate, and substrate surface. Wettability is the angle of contact between the solder and the substrate. It has been on record that the smaller the wetting angle, the better the wettability of solder [2]. Wettability of the solder also explains how easy the Sn-Cu solder flow on top of substrate surface, the connection between Sn-Cu solder and its substrate surface determines the quality of the wetting [3]. This is characterized by the capillary action of the substrate and surface tension. It has been well known that wettability and spreadability are the most significant properties in the soldering process and microelectronic packaging reliability.

In recent years, many scholars have conducted extensive research on the solderability and wettability of lead-free solders. Wang *et al.* [4] studied the correlation between spreadability and wetting driving force of Ni-GNSs reinforced SnAgCuRE composite solder through Young's equation and found that the contact angle between solder alloy/Cu substrate surface and the surface tension have similar trend. Lin *et al.* [5] presented a wetting of Ni-based amorphous and crystalline alloys by Sn-based solders and affirmed that alloys of similar properties have the better wettability which can be improved upon by the surface energy as well as crystallization that occurs during wetting of substrate.

Han *et al.* [6] investigated on early wetting and interfacial behavior of Sn-based solder on Cu substrates with different roughness on early wetting behavior and interfacial reaction under atmospheric conditions. It was reported that with a roughness range between 0.320–0.539 μm , the solder is distributed in an elongated shape as it were reported within the roughness ranging from 0.029–0.031 μm .

According to their findings, the solder spreads in the direction of grinding process thereby forming a circle that is properly formed. In another further research, Dharma *et al.* [7] reported on the relationship between the wettability of lead-free solder alloys and surface tension through Young's equation and found that the contact angle between solder alloy and the Cu substrate surface were correlated.

Other researchers have found that good wetting angle and cooling rate data in Bi-, Zn-and Sn-based solder alloys [8]. In their findings, it was affirmed that an adequate wetting is essential to generate high-quality solder connections and that the wetting angle is paramount to have good wettability. In their report, the most accepted idea is that wetting angle may influence the ability of heat to flow between the liquid solder and substrate surface. Shen *et al.* [9] mentioned that the contact angle between the liquid solder and the substrate may also improve the wettability. In another report, Abdullah *et al.* [10] presented an extensive review on composition of Sn-Cu solders to improve the wettability of Sn-Cu solders. In their findings, good modification of copper substrate with good wettability can improves the mechanical properties of the substrate.

Further research has shown the spreadability of a Sn-based solder on the substrate that the direction of the spreading during wetting is liable to move to the surface of the substrate [11]. Kotadia *et al.* [12] reported the formation of interfacial IMCs and growth between various solders and substrates and reported that importance of each stage in a soldering process depends on the solubility which can resulted to good wettability of solder on substrate surface. Li *et al.* [13] studied laser-induced wetting behavior of AlSi5 alloys on Ti6Al4V substrates with various micro textures that was investigated. In their findings, good wettability was also recorded due to the increase in surface energy of the substrate.

Chen *et al.* [14] reported that movement of solder during wetting may occurred in an horizontal direction which gives room for good wettability. Previous studies

have also shown that wetting time, force and angle are important parameters that may result to good wettability [15]. In a latest research, Huan *et al.* [16] reported that the surface modification of substrate can be done, and wettability of substrate can be improved significantly. Wang *et al.* [17] investigated the wetting behaviors of Sn-5Sb-CuNiAg solders on substrates in different soldering processes and the effects of alloying elements on the wettability. Their findings reveal that the effects of different soldering processes and alloying elements on the wetting behaviors of Sn-based solders on Cu substrates was quite satisfactory.

In another recent report, Shen *et al.* [18] reported a lower wetting angle of (19.0°) of Sn-based solders with copper substrate. In a recent study, Sn-based solder has recorded good wettability with copper substrate due to a good diffusion property it possessed [19]. Lin *et al.* [5] also reported good wettability of Sn-based solder with copper substrate. Wang *et al.* [20] also recorded lower wetting angle of (69° and 80°) > 0 and < 90° in Sn-based solder on copper substrates. Soares *et al.* [21] in their recent study has shown that Sn-Cu solder with copper substrate gives good account of wettability. Previous record also affirmed that Sn-Cu solder are commonly used in soldering techniques due to its low melting temperature of (227°C) and ability to possess good wettability and low-cost [22-25]. Sn-Cu solder has received great attention in a soldering process due to its good wettability with substrates [21–25]. The recent report has established that Sn-Cu solder and copper substrate are the perfect match to achieve good wetting when an effective soldering process is required in electronic industry.

The hypothesis of this study projected that substrate surface profile parameters (primary) have a dominant influence on wetting behaviour. Measurements of wetting angles of contact using Image-J software is dynamically characterized by spreading process of the Sn-Cu solder on substrate surface with multiple viewing angles. The dynamics wetting angles of Sn-Cu solder were having a corresponding relationship with copper substrate, which serves as a fundamental reliability of the Sn-Cu/Cu substrate solder joints.

In the previous research, there is lack of quantitative data on the wetting dynamics of Sn-Cu solder on copper substrates. The previous studies has not recorded optimization of soldering technique by investigating correlation between surface profile parameters (roughness, waviness and primary) that gives wetting dynamics of Sn-Cu solder on modified copper substrate. This paper has given justification to optimization of soldering technique by metallurgical approach through rotational grinding process that creates copper substrate surface which resulted to a dynamic wetting.

This work is relevant in electronics industry and metallurgical joining applications in order to improve the printed circuit board PCB etching process or soldering efficiency.

2.0 METHODOLOGY

2.1 Materials Preparation

To prevent non-reliability of the solder joints that may cause intermittent or complete failure of the connection and may also cause noise or distortion in electronic circuit, a commercially available as received (99.9%) copper plates of size 450 × 450 × 5 mm³ were used as a substrate material in which its surface was modified. A waviness parameter was chosen to qualify and quantify the modified Cu substrate.

A Sn-Cu (SC) solder flux with model, SC G227 was used for the soldering technique in this study. It is a very soft solder wire with diameter of 0.8mm and alloying composition of 0.7%Cu, 99.3%Sn. A solder machine Pruntop 8586D+ model comprises of the solder iron was also used. A direct hand soldering technique was employed by making a direct contact between the soldering machine and the solder iron. The soldering machine is to supply the required melting temperature needed to melt the SC solder wire into liquid and went through pre-heating of the Cu substrate before the deposition of solder melt.

2.2 Surface Profile Parameters

Surface Profile Parameters such as waviness and primary are used to optimize soldering process. They characterize the surface finishing in terms of roughness and smoothness during the grinding process.

2.2.1 Surface Profile (Waviness)

This is irregular wave pattern which deviates from the original substrate surface. It gives deeper profile depth with longer wavelengths compared to roughness substrate surface.

2.2.2 Surface Profile (Primary)

Primary profile is characterized by the features of roughness and waviness and therefore form a complete image of the surface topography.

2.2.3 Method used for quantification of Profile Parameters

Alicona Infinite Focus Microscope IFM was employed to quantify the substrate surface profile (roughness, waviness, and primary). It involves the use of light as an optical microscope. As the laser or beam of light passes through the optical sensor of the IFM, the light showered on the sample were reflected back through the IFM sensor. The reflected light or ultrasonic waves are measured by the microscope to detect differences of the apparent images and that of object which are then used to measure the surface roughness, waviness and primary profile of the samples respectively. When the light shower on the

sample, it passes through the optical sensor and reflected back through the IFM sensor. This allows the evolution of the three-dimensional 3D as well as Two-dimensional 2D images of the sample and individual grains of full 3D and 2D distinguished and the kinematics of all the grains were displayed on the screen of the microscope. This were separated automatically by the microscope in-built software and the measured values of (roughness, waviness and primary) were kept in record.

2.3 Experimental procedures and characterization of the wetting

Soldering was carried out in Microelectronic Packaging and Materials Laboratory at Institute of Microengineering Nanoelectronics (IMEN), UKM at Selangor, Bangi, Malaysia, at room temperature ranges from 28-30°C, and Humidity at average of 82%. The experimental procedure encompasses of SC solder flux that was put in to contact with the solder iron of the soldering machine. The solder machine was set to a temperature of 340°C that is above the melting point of SC solder wire. The heated solder wire melts and pour on the surface of the modified substrate surface that contains a peculiar different surface conditions created by SiC abrasive grits of different grades of 400, 600, 800, 1000 and 2000. Upon contact with the Cu substrate, the molten solder initially formed a spherical droplet. However, after approximately 5 seconds, it transformed into an elliptical or semicircular shape resembling half of a circle and subsequently spread uniformly across the substrate surface, forming a consistent wetting pattern. Figure 1 presents the schematic diagram of the soldering system.

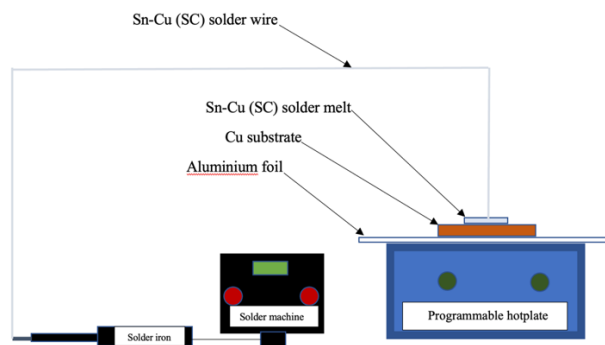


Figure 1 Schematic diagram front view of the soldering assembly of molten Sn-Cu solder wire on different substrate surface ranging from: 400, 600, 800, 1000, 1200 and 2000 as it was carried out in this present study

Characterization of the wetting of the Cu substrate surface condition was carried out using Image-J software. The spreading area on the substrate surface were characterized by taken the measurement data in the average of eight measurements, to ensure the accuracy of the measurements. A very recent and

the version of Image-J software (64-bit, java 8) software was used in this study. The successive wetting angles on each of the substrate surface were taken by Image-J software. A soldered image as it were presented in Figure 2, were imported into the software. The three coordinate points of an inclined angle which the solder made with the Cu substrate were selected at points (a), (b) and (c) Analyse and measure botton were selected. Measurement was taken from both left-hand side and right-hand side to ensure precision and accuracy and the authentication of the spreading area or the wettability of the solder on substrate. After the measurement, the results of the contact angles were displayed on the screen. The projected angles that solder made with the substrate surface (400 – 2000) and the three coordinate points that produced angle of contact were shown in Figure 2.

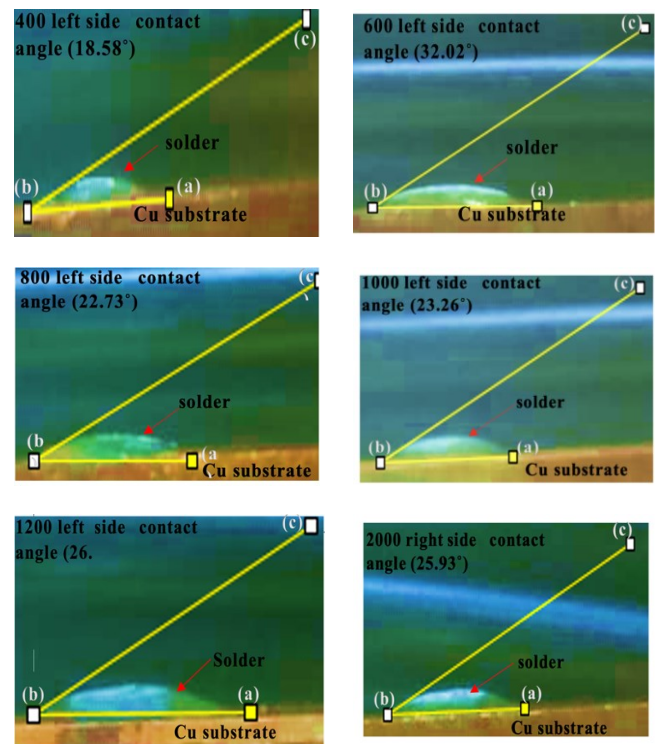


Figure 2 Measurements of the contact angle with respect to substrate surface profile of 400R, 600R, 800R, 1000R, 1200R, and 2000R. Each substrate surface was measured at left sides, giving equal angles

3.0 RESULTS AND DISCUSSION

3.1 Solder Spreading Behaviour

The solderability of a surface is based on the speed and reliability by which it is wetted by the molten solder using a given flux. Although, the milder the flux, the higher the solderability of all the surfaces involved [23]. Solderability is one of the most important parameters in all soldering processes, it is much essential to have a meaningful and reproducible

method for measuring solderability, but in the case of hand soldering (employed in this study), it was mainly the flux vendors who measured solderability in order to assess the ability of their activated fluxes to cope with the often indifferent solderability of component wires and soldering lands. Therefore, based on the research done by Strauss *et al.* [26] it is not required to measure the solderability of Sn-Cu solder on substrate surface in this study.

A conventional model for spreading on rough surface presented by Kumar and Prabhu *et al.* [27] was adopted in prior to the soldering process. The spreading of the Sn-Cu molten flux on a substrate surface occurred by three stages: the first stage is the transport of the Sn-Cu molten flux from the vertical direction to the top of substrate surface. The second stage is the spreading of the molten droplet on the substrate surface along the horizontal axis within the spherical diameter of the drop of the solder. The third stage is the horizontal spreading along an extension or additional area caused by the substrate surface as it indicated in Figure 3.

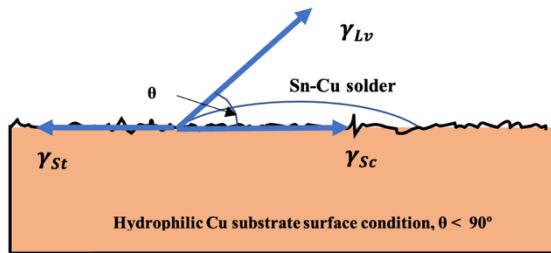


Figure 3 Schematic diagram of Sn-Cu solder droplet contact angle on hydrophilic substrate surface.

In Figure 3, Young's equation is applicable in which the contact angle θ of the molten Sn-Cu solder on the substrate surface is determined by the interfacial tension, as shown in equation 1 [4].

$$\cos \theta = \frac{\gamma_{Lv} - \gamma_{Sc}}{\gamma_{St}} \quad (1)$$

In equation 1, γ_{lv} , γ_{sc} , γ_{st} respectively represents the three modes of spreading on hydrophilic substrate surface. It is a sequential process that follows the kinetic, thermodynamic and hydrophilic phenomenon. The spreading is a physical process through which liquid wets the substrate surface. The increase in the area of coverage by the Sn-Cu molten solder with respect to substrate surface represents the drop at time of initial drop and spreading on the substrate. The continuous decrease in the contact angle and continuous increase of the base diameter when in contact has eventually shown a progressive spread of Sn-Cu solder on the substrate surface as shown in Figure 3.

Figure 4 presents the wettability results of Sn 0.7% Cu 99.3% solder on substrate surface as a result of conventional model adopted. It could be seen that

the wettability of the Sn-Cu solder was very effective and excellent on the substrate surface. It was observed that the wettability of Sn-Cu solder on its substrate is dynamic. The reason for this is due to the different substrate surface profiles (roughness, waviness and primary) that gives different depth during the substrate surface modification. The different depth profile in a dynamic behaviour may be also attributed to some factors that may affect the modification process such as: (contact pressure, speed of the grinding wheel, time of contact etc.) as it were presented in Figure 4.

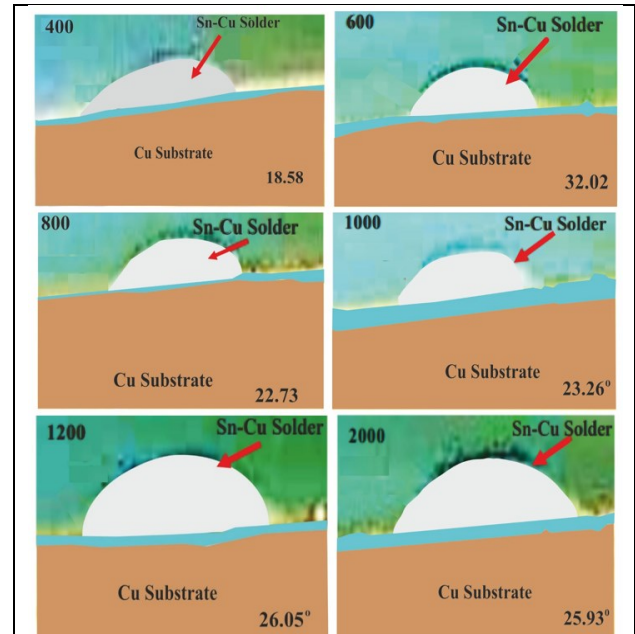


Figure 4 Wettability of Sn 0.7% Cu 99.3% solder on substrate surface profile

In Figure 4, the Sn-Cu solder spreading on Cu substrates with different substrate surface profile was examined from (400 – 2000) substrate surface profile. It is understood that the Sn-Cu solder prefers to spread along the horizontal axis, which causes white line between the Sn-Cu solder and substrate surface profile when Sn-Cu solder spreads over hydrophilic surface of substrate surface profile. The liquid metal has flown easily along the horizontal axis is because the Sn-Cu solder has easily overcome or penetrated through the barriers between the Sn-Cu solder and the hydrophilic surface of substrate surface profile. The easy spreading is due to the creation of effective substrate surface profile ranging from (400-2000) as a modified surface. Furthermore, it can be noticed that as the substrate surface profile increases, the spreading area increases and decreases in a dynamic form as thus: (400 substrate surface profile gives 18.58° contact angle), (600 substrate surface profile gives 32.02° contact angle), (800 substrate surface profile gives 22.73° contact angle), (1000 substrate surface profile gives 23.26° contact angle), (1200 substrate surface profile gives 26.05° contact

angle) and (2000 substrate surface profile gives 25.93° contact angle).

In Figure 4, it was also revealing the spreading manner of Sn-Cu solder along the horizontal axis and the penetration downward through the hydrophilic substrate surface profile (400 μm) that gives a smaller contact angle of 18.58°, with much more pronounced penetration depth and most spread. The spread and penetration in (600 μm) substrate surface profile was decreased with increase in contact angle (32.02). The angle of contact in in (800 substrate surface profile) was decreased to (22.73) with more pronounced penetration depth and more spread compared to (600 substrate surface profile). There is a very little difference between (1000 substrate surface profile) and (800 substrate surface profile) as the angle of contact in (1000 substrate surface profile) was a little bit increased to (23.26) with lesser penetration depth and spread compared to (800 substrate surface profile). It is also very glaring from Figure 4 (1200 substrate surface profile) gives lesser spread and penetration depth with increase in contact angle of (26.05) compared to (1000 substrate surface profile). Finally, from Figure 4, (2000 substrate surface profile) gives more spread and deeper penetration depth with decrease in contact angle of (25.93) compared to (1000 substrate surface profile).

In this present study, the spreading of Sn-Cu solder on each substrate surface profile adequately behaves according to the status of substrate surface profile that was established in our previous study. This trend and the chain of linkage is hopefully to continue in our next future study.

3.2 Surface Profile Effects on Wetting Dynamics

When the substrate surface profile value is too high enough, the kinetic energy is set in to move the molecules of the solder along the substrate surface profile within the ball of the solder which resulted to the cohesive force of the molecules of the solder ball drop [24], this action combines with the adhesive force between the solder ball and the substrate surface profile to enable the successive movement of the solder ball drop. After the drop contact, the spread was extended to the surface area within the diameter ball of the solder due to the cohesive forces within the solder ball diameter as it was earlier discussed in Figure 3 [27]. Due to the substrate surface profile that was created for the purpose of good solderability and wettability before the commencement of the soldering process, the wetting has extended to the additional area beyond the diameter of the solder oval or eclipse shape that finally formed a glide with a very low contact angle which resulted to an excellent wettability. The additional area of wetting added due to the substrate surface profile has also causes increase in surface energy that contributed to an excellent wettability [24]. Increase in surface energy also make it to create a solid bond attraction between the Sn-Cu solder and the substrate surface profile as it were presented in Figure 5.

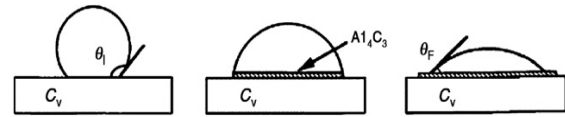


Figure 5 Model for reactive wetting (stages of reactive wetting of liquid of Sn-Cu solder on Cu substrate surface condition) [27]

In Figure 4, there are some factors that affect the wettability of Sn-Cu solder on the substrate surface profile as established by Kumar & Prabhu [27] that wetting is affected by large number of factors including liquid properties, substrate properties and system conditions and the effect of these factors on wettability is discussed. Though, it is difficult to determine the exact mechanism that controls the kinetics as wettability is determined by some factors such as: diffusion of Sn-Cu solder in to the substrate surface, force of gravity that aided the vertical movement of molten solder to drop on top of the substrate surface, dissolution of the atoms of Sn-Cu solder in the matrix of the copper substrates and some other factors such as hydrophobic or super hydrophobic nature of the substrates. Other factors such as hydrophilic or super hydrophilic, capillary or surface tension on the substrates are paramount [27–30]. The solidification of molten solder after wetting of contact finally gives a strong tie. In Figure 4, the kinetic of wetting on substrate surface profile solely depends on its hydrophilic nature. During the soldering process, Sn-Cu molten solder due to the latent heat of fusion, was adequately absorbed and spread by the hydrophilic nature of the substrate surface profile. The molten solder changed from its spherical shape to an oval shape and finally to a glide shape. For practical purposes, the liquid is said to wet the surface of solid when the contact angle is less than 90° [27]. This present study has justified that all the substrate surface profile has an excellent wettability with very low contact angles (> 0 and $< 90^\circ$). In addition, it is important to know, that substrate surface profile modified in this study has already removed the oxide film layer on the surface of the substrate surface profile before the commencement of the soldering, this is contributing factor to the enhancement of the solderability and the wettability of the Sn-Cu solder.

Thermodynamics also play a role in the solderability and wettability of the Sn-Cu solder on the substrate surface profile in reactive environment as the molten solder get spreading and transport at the Sn-Cu molten solder/ substrate surface profile interface. A chemical reaction has occurred between the Sn-Cu solder and substrate surface and form chemical bonds which are responsible for wetting. As the solid of the melt formed, an interface is created between the solid and the remaining liquid form. A surface free energy (σ) is associated with this interface, as the larger the wetting area, the greater the increase in surface energy as reported by Stammitti-Scarpone et al. [31].

In addition, Gibb's free energy of the reaction ΔGr is related to the equilibrium constant of the reaction as follows.

$$\Delta Gr = \Delta Gr.\theta + RT \ln K \quad 2$$

At equilibrium state when the process of wetting is completed, the equation 2 becomes:

$$\Delta Gr.\theta = -RT \ln K \quad 3$$

From equation 3, according to conventional thermodynamics approach, the wetting of Sn-Cu molten solder is possible if the ΔGr for the interfacial reaction is negative (-ve) as the heat energy was given off completely which led to a solidification process after a complete wetting. From equation 1, the values of substrate surface profile (roughness) are: 0.26, 0.17, 0.62, 0.37, 0.12 and 0.12 μm . That of substrate surface profile (waviness) are: 0.18, 0.11, 0.35, 0.13, 0.08 and 0.04 μm while the values of substrate surface profile (primary) are: 0.36, 0.21, 0.68, 0.44, 0.18 and 0.12 μm .

Hence, the value obtained obeys young's equation if recall from equation 1,

$$\cos \theta = (\gamma_{Lv} - \gamma_{Sc}) / \gamma_{St}$$

Therefore,

$$\gamma_{Lv} \cos \theta > 0 \quad 4$$

From equation (1) and (4), the angle of contact of the Sn-Cu molten solder is the difference in the spreading of the molten droplet on the substrate surface along the horizontal axis within the spherical diameter of the drop of the solder and the horizontal spreading along an extension or additional area caused by the Cu substrate surface condition. This becomes:

$$\gamma_{Lv} \cos \theta = \gamma_{St} - \gamma_{Sc} \quad 5$$

Another factor that responsible for the excellent solderability and wettability is a good surface tension that was firmly established through a capillary rise action in a substrate surface profile. The good capillary-rise ability implies that the modified hydrophilic substrate surface has indeed led to a well-established surface tension after the establishment of the good solderability and wettability that established in equation (5). Equation 5 has also justified a complete dynamics wettability of Sn-Cu solder on modified copper substrate.

This section presents the discussion on correlation between wetting contact angle and substrate surface profile. In Figure 6 to 8, the correlation between wetting contact angle and substrate surface profile are investigated. Analysis performed shows data of wetting (contact angle) on the vertical

axis and paper size/substrate surface profile on the horizontal axis which are graphically represented by scatterplot.

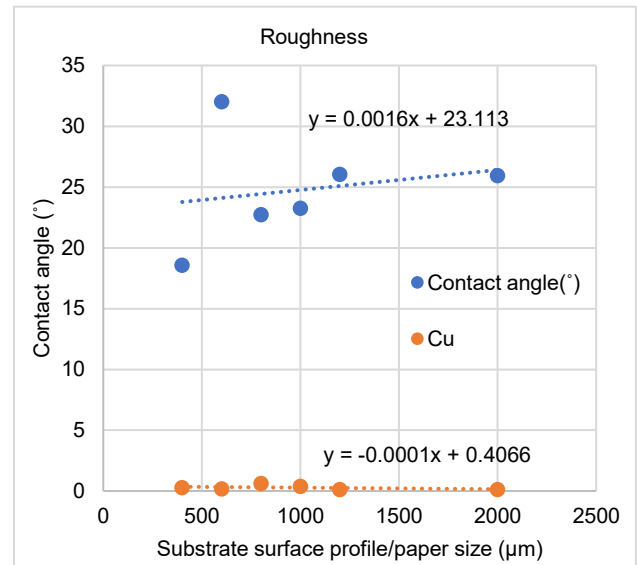


Figure 6 Relationship between the wettability contact angle of Sn-Cu solder and substrate surface profile (roughness)

From Figure 6 (roughness), the scatter plot has formed a linear relationship between wetting contact angle and substrate surface profile. Based on this linearity of the slope, we can determine the direction of the relationship between wetting contact angle and substrate surface profile. The slope S_w is the slope for wetting (contact angle) which is ($S_w = 0.0016$) and slope S_c substrate surface profile is ($S_c = -0.0001$). The value of the slope in wetting (contact angle) indicates positive (+ve) relationship ($S_w = 0.0016$), even though it is a very weak positive relation with the substrate surface profile. The fact has been established that in roughness profile, as the wetting angle of contact increases or decreases, the substrate surface profile (roughness) tends to increase or decreases. This makes the Sn-Cu solder wetting angle of contact to be dynamic with substrate. The value of the slope in substrate surface profile (roughness) indicates negative (-ve) relationship ($S_c = -0.0001$), even though the slope line is almost run through the same horizontal axis of the substrate surface profile. This reveals that there is no much deviation between Sn-Cu solder wetting angle of contact and substrate surface profile as they were actually giving correlation signals and the different surface profile depth is dynamically influenced the wetting angle. However, the negative (-ve) relationship indicates that both wetting contact angle and substrate surface profile moves in opposite directions indicating a negative (-ve) correlation. This of course, enable good wettability to occur between Sn-Cu solder and substrate surface. This finding also signifies a trade-off between wetting contact angle and substrate surface profile, where a decrease or increase in wetting contact angle is solely depends on

the increase or decrease in substrate surface profile (roughness) as per paper size ranges from 400, 600, 800, 1000, 1200 and 2000 with very small corresponding wetting contact angle. This indicates a good wettability of Sn-Cu solder on a substrate surface profile as they are > 0 and $< 90^\circ$. This agree with the records in the literature that the smaller the wetting angle of contact, the good is the wettability.

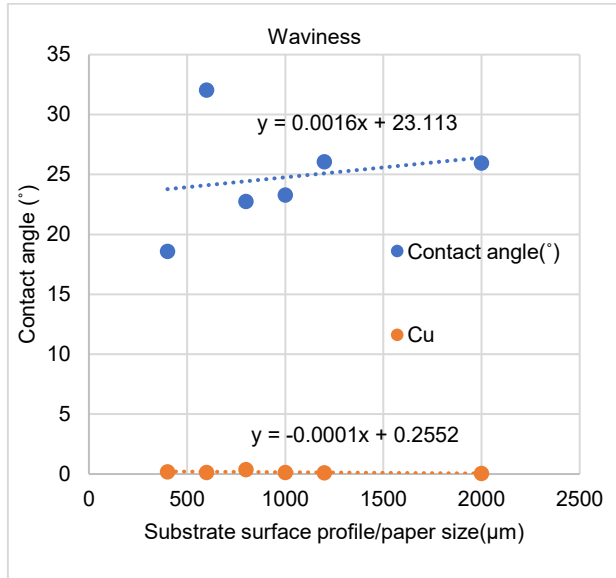


Figure 7 Relationship between the wettability contact angle of Sn-Cu solder and substrate surface profile (waviness)

From Figure 7, the relationship of wetting contact angle and the substrate surface profile (waviness) is the same with that of substrate surface profile (roughness), there is nothing change as substrate surface profile (waviness) measurement has no obvious impact to change the wetting angle. The same is applicable to substrate surface profile (primary) in Figure 8. This implies that substrate surface profile parameters (roughness, waviness and primary) give same behaviours relating with the wetting angle of contacts. A correlation equation was established between solder wettability and substrate surface profile, with correlation coefficients of $r = 0.18$ (roughness), $r = 0.11$ (waviness), and $r = 0.22$ (primary), showing that there is correlation between the wetting contact angle and substrate surface profile indicating that the surface profile (primary) most influences wettability.

The reason why there are weak correlations is that patterns of the surface roughness were transferred from SiC abrasive grit paper into Cu substrate surface through the mechanical rotational grinding process which does not involve a direct stamping. However, a direct stamping process could have given a stronger correlation. This is also contributed to why the measurement is so dynamics which also give dynamics wetting. This occurred due to the new

creativity applied in this present study which gives an excellent wetting.

This present study has recorded the dynamics wetting which established that wettability of Sn-Cu solder on substrate surface may be dynamics, not necessarily follow the trend of either continuous increase or decrease in surface measurement. It also established that substrate surface profile (primary) has the highest correlation value indicating that it is most influences the wetting.

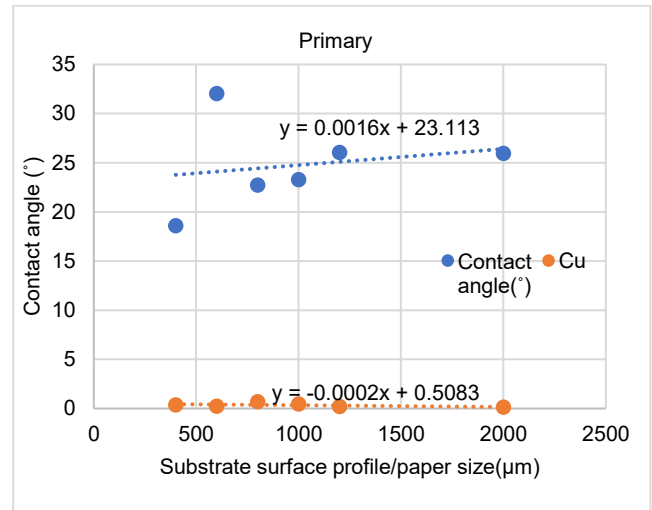


Figure 8 Relationship between the wettability contact angle of Sn-Cu solder and substrate surface profile (primary)

The new understanding obtained from this finding is that substrate surface profile parameters within the range of (400, 600, 800, 1000, 1200 and 2000) grit abrasive paper and within the experimental procedures and condition in this study can produce excellent dynamics wetting of Sn-Cu solder on modified copper substrate.

4.0 CONCLUSION

This present study has established that there is a correlation between surface profile parameters and wetting dynamics of Sn-Cu solder on modified copper substrate. A correlation equation was established between solder wetting angle and substrate surface

profile, with correlation coefficients of $r = 0.18$ (roughness), $r = 0.11$ (waviness), and $r = 0.22$ (primary), indicating that the substrate surface (primary) is most influences the dynamics wetting angle of Sn-Cu solder. The correlation between Sn-Cu solder and substrate surface has been established through a dynamic wetting angle of contact (18.58° , 32.02° , 22.73° , 23.26° , 26.05° and 25.93°) that are > 0 and $< 90^\circ$. These results are useful in the electronics industry to improve Sn-Cu solder joint reliability.

It is important to acknowledge that these conclusions are drawn from a specific range of grit sizes and experimental conditions. A Sn-Cu solder flux with type SC G227 was used for the soldering technique in this study. It is a very soft solder flux with thin diameter of 0.8mm and alloying composition of 0.7%Cu, 99.3%Sn. Future research may still test hard Sn-Cu solder flux with bigger diameter and different flux composition. In addition, further investigation with different parameters or materials could yield additional insights.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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