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Comparative Wetting Study of Sn-0.7Cu Solder on Dimple and Pillar Micro-Texture Fabricated by the Photolithography Technique

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ABSTRACT

The study focused on exploring the impact of micro-textured surfaces on the wetting behaviour of Sn-0.7Cu solder. Dimple and pillar micro-textures, each with a diameter of 100 µm, were fabricated on the copper substrate using a photolithography technique. The Sn-0.7Cu solder was melted onto the micro-textured copper substrate during the soldering process. The spreading time, spreading area, and spreading rate of the solder on the copper substrate were investigated. The copper substrates with dimple textures exhibited a prolonged spreading time of 51 seconds, a smaller spreading area of 60.54 mm², and a slower spreading rate of 1.44 mm²/s than the pillar-textured copper substrates. However, the presence of micro-textures resulted in a reduced spreading area, indicative of enhanced solderability. This improvement is attributed to the textured substrate promoting higher copper diffusion during the soldering process. The controlled application of micro-textures holds promise for optimising wetting behaviour and solderability in electronic assembly processes, presenting avenues for further exploration and application in the realm of materials science and electronic manufacturing.

Keywords: *Soldering, Sn-0.7Cu, Micro-texture, Dimple, Pillar, Wetting, Photolithography*

1. INTRODUCTION

The wetting tendency of solder denotes its capacity to spread and adhere to the surface of the substrate during the soldering process [1]. This is a crucial aspect in establishing a bond between two metal surfaces. The spreading time of solder signifies the duration required for molten solder to uniformly spread and wet a surface, which in turn influences the resulting bond formation. Solder with effective wetting ability will evenly cover the substrate, establishing a robust and reliable bond. On the other hand, poor wetting can result in weak bonds, solder bridging, and other defects [2]. Understanding the degree and speed of wetting is essential for ensuring high-quality bonding performance. The degree and speed of wetting are typically used to characterise wetting phenomena, with the rate at which liquid solder wets indicating how quickly it spreads across the substrate. The spreading areas of solder alloys are influenced by various factors, including surface roughness and the properties of the solder alloy [3-5].

Numerous strategies have been explored to develop lead-free solder alloys with properties comparable to Sn-Pb solder alloys but with reduced toxicity. The eutectic tin-copper (Sn-0.7Cu) alloy is a candidate for replacing Sn-Pb solder due to its high availability and low production costs. In addition, the eutectic alloy has advantages such as a low melting point, a narrow crystallisation temperature range, good fluidity and a low tendency for hot cracking and segregation. However, Sn-0.7Cu solder exhibits poor wetting properties, affecting solder joint quality. Achieving proper wettability is crucial for adequate bonding; therefore, micro-textured surfaces are proposed to enhance the wettability and spreadability of the Sn-0.7Cu solder alloy [6].

Textured surfaces significantly influence wetting behaviour, surface energy, and surface area, subsequently impacting solder wettability. Researchers employ diverse methods to create surface textures, such as surface peening, laser surface texturing (LST) [7-9], lithography [10-11], electrochemical machining and wet chemical etching [12] with photolithography recommended. Photolithography is more straightforward, efficient, reliable, and less expensive than other lithography methods. It also offers high precision, high resolution, and high dimensional stability [13]. Photolithography involves the precise transfer of a pattern onto a substrate through a sequence of steps, including photomask design, photoresist coating, exposure, development, and etching [13]. Achieving high resolution and precision, along with ensuring uniformity throughout the fabrication process poses challenges.

Micro-textures may provide capillary channels facilitating flow and promoting wetting. However, consensus is lacking on how photolithography-based micro-texture fabrication influences solder wetting, emphasising the need to investigate the spreading and spreadability of Sn-0.7Cu solder on textured copper substrates. In this study, photolithography-based surface modification of copper was employed with different geometries on the substrate. Exploring the impact of micro-textured surfaces on the solderability and wettability of Sn-0.7Cu solder is worthwhile because such surface modifications can enhance the wettability of lead-free solder liquids and facilitate the diffusion of copper within the solder.

2. METHODOLOGY

This study used a 15 mm × 15 mm × 1 mm dimension of high-purity copper plate (99.9 %) as the substrate and the Sn-0.7Cu as the lead-free solder alloy. The photolithography technique was carried out to fabricate micro-textures on the copper substrate. Two different geometries of micro-texture were produced: dimple and pillar, as shown in the schematic diagram in Figure 1. In the photolithography, the copper plate was first ground and polished until a smooth mirror-like surface was formed before the process started. The fabrication method includes photoresist coating, spin coating, soft baking, UV exposure, development, etching, and stripping off. The features of the micro-textures produced are listed in Table 1.

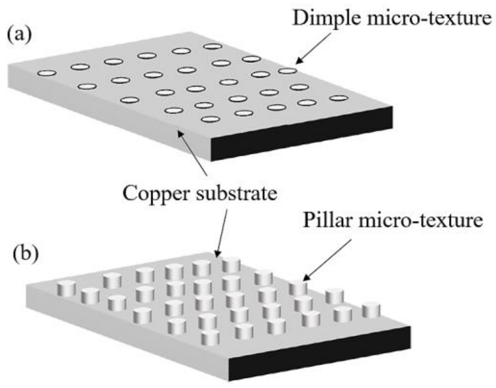

Figure 1. Schematic diagram of (a) dimple and (b) pillar micro-texture on copper substrate.

Table 1 The features of micro-textures

Micro-texture	Sample	Diameter (μm)	Distance (μm)	Depth (μm)	Height (μm)
Dimple	T_{D100}	100	300	25	-
Pillar	T_{P100}	100	300	-	25

2.1. Photoresist Coating

In the photoresist coating process, the copper substrate was placed on the vacuum chuck, and the positive photoresist with an amount of 4 ml was applied onto the copper substrate using the resist dispenser. Then, the spin coating process was carried out at a rotating speed of 850 rpm for 15 seconds at the beginning, then increased up to 3000 rpm for 30 seconds. After that, the soft bake process was conducted place to evaporate any remaining solvent from the photoresist. The samples were preheated at 90 °C – 100 °C to evaporate any remaining solvent on the copper surface.

2.2. Exposure and Development Process

The photomask and photoresist-coated sample were placed and aligned together on the photolithography mask aligner for the pattern-transferring process. Then, the substrate was subjected to a development process. In the development process, the Resist Developer RD-6 was used as the substance. The coated sample was immersed in the RD-6 to dissolve the unexposed part of the positive photoresist for a duration ranging from 30 to 200 seconds. Afterwards, the samples were washed directly using deionised water to remove any excess developers on the substrate.

2.3. Etching and Strip-Off Process

The samples were immersed in a ferric chloride (FeCl3) solution for the etching process. The etching duration ranged from 15 minutes to 45 minutes. The remaining photoresist was stripped off using acetone to remove the excess photoresist on the sample's surface. Subsequently, the sample was air-dried at room temperature before advancing to the soldering process.

2.4. Soldering Process

Approximately 0.4 g of solder sheet was placed on the copper substrate to measure the spreading area and flow rate, and a small amount of RMA flux was applied before the melting process. The sample was melted using a hot plate, and a thermocouple was used to monitor the temperature. The temperature profile used was similar to the reflow profile of the lead-free solder (Figure 2). The time taken for the solder to melt was measured and recorded, starting at the reflow temperature and ending at the peak temperature indicated by the reflow profile. Once solidified, the spreading area of the solder bump on the textured copper substrate was measured using Image-J software. The spreading rate of solder on copper substrates was also calculated based on the recorded time during the solder's wetting and solidification process.

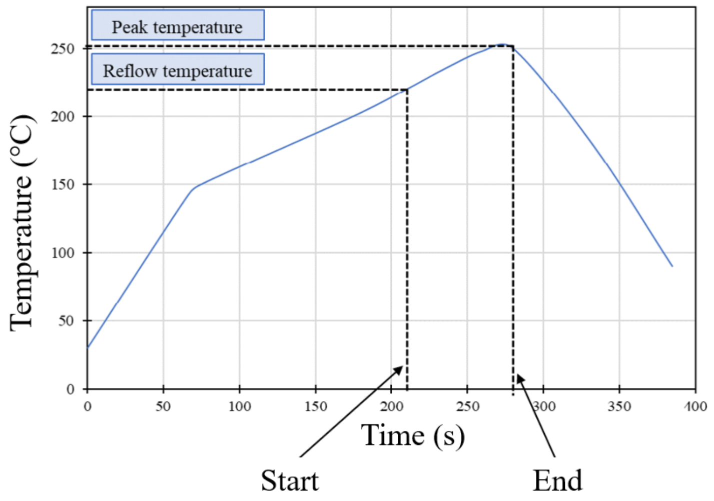

Figure 2. Heating profile of Sn-0.7Cu solder alloy.

3. RESULTS AND DISCUSSION

3.1. Surface Morphology of the Micro-Textured Substrate

The surface morphology of the micro-textured substrate plays a crucial role in influencing the wetting behaviour of the solder. The dimple and pillar micro-texture were found to be the most common geometric features for surface patterning as they could be arranged evenly and distributed well on the substrate surface. These micro-textures increase the surface area of the copper substrate which in turn has beneficial effects on the properties of the substrate. It can be observed in the analysed images of the dimple micro-texture (Figure 3(a) and (b)), and pillar micro-texture (Figure 4(a) and (b)) was completely smooth, with no ridge or burr on the edge of the micro-dimple, and deposited substrate materials were observed on the copper substrate.

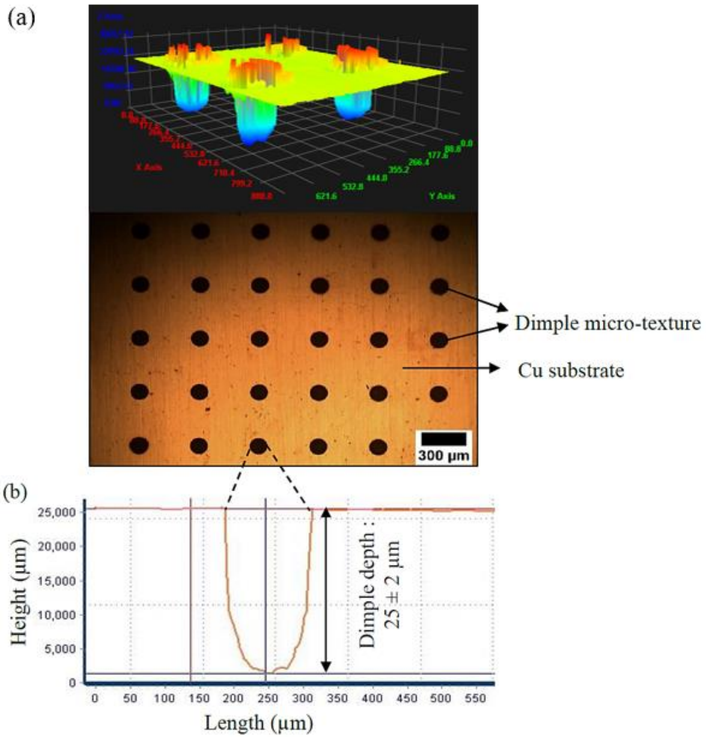

Figure 3. Surface morphology of dimple micro-textured substrate, (a) 2-D and 3-D image of dimple textured copper substrate, (b) the dimple profile.

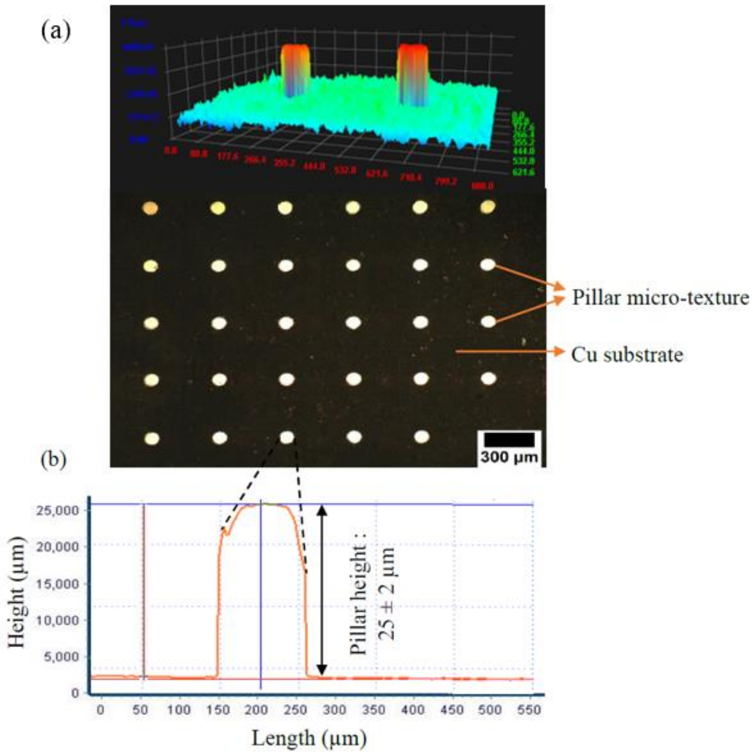

Figure 4. Surface morphology of pillar micro-textured substrate, (a) 2-D and 3-D image of pillar textured copper substrate, and (b) the pillar profile.

Compared with the dimples fabricated using laser surface texturing, the photolithography technique has been proven to provide a smooth surface finish on copper surfaces [14]. Besides that, consistent dimple depth and pillar height at 25±2 µm demonstrated that photolithography can provide excellent control of the desired feature. The process is also an intriguing approach for optimising surface patterns and fundamental studies due to its high precision, high resolution, and freedom of shape.

In the photolithography, the condition of the copper substrate was strictly influenced by the etching process. This etching process ensures stress-free surfaces without altering the material integrity. Generally, more etching duration was required for a larger etching area due to the continuous dissolution of atoms of the exposed area of the copper substrate. For the pillar micro-texture, a longer etching duration was required compared to dimple micro-textures with the same diameter and depth/height to achieve the desired shape and dimensions.

3.2. The Time and Area of Spreading of Sn-0.7Cu Solder

Understanding the spreading characteristics of solder on different textured surfaces is crucial for evaluating the potential improvements in wettability and bond formation. The spreading time provides valuable insights into the ability of the solder to establish a strong bond and its propensity for creating defects such as solder bridging. In addition to the spreading time, the area covered by the solder after spreading helps to assess the extent of wetting and coverage achieved by the solder on the textured surfaces. The spreading time refers to the time taken, while the spreading area of solder refers to the surface area covered by the molten solder during the soldering process.

The spreading tendency of solder during the soldering process is strongly influenced by the presence of impurities or contaminants on the substrate [15]. Figure 5 illustrates the spreading of Sn-0.7Cu solder on the dimple-textured copper substrate. The first spreading profile represents the solder before it melts. The next profile shows the spreading of the solder sample as the temperature rises from the melting temperature to the peak temperature. The latter two profiles depict the spreading at the peak temperature. The final contour represents the spread area after the completion of spreading. As observed in Figure 5(a), the solder alloy melts and spreads uniformly in a form resembling almost a circular shape. It was observed that the spreading of Sn-0.7Cu solder spanned 51 seconds from initiation to solidification. Initially, the solder melted in 4 seconds, forming a spherical droplet on the copper substrate in 14 seconds. The molten solder then spread out, increasing the contact area between the solder and the copper substrate, as evident 44 seconds into the spreading process. For a dimple micro-textured copper substrate, the molten solder penetrated and became trapped in the dimple cavities due to capillary action [3], and then continued to spread. Consequently, spreading on the dimple-textured surface is comparatively smaller due to the higher volume of molten solder required to fill in the dimple. This leads to a low volume of molten solder remaining on the surface.

For the pillar-textured copper substrate (Figure 6), it was observed that the Sn-0.7Cu solder fully spread on the surface in 43 seconds. Similar to the dimple micro-textured copper substrate, the spreading exhibited consistent melting and spreading, with robust spreading observed during the initial stages. After extending the spreading time to 51 seconds, a reduced spread was observed, signifying that significant spreading did not occur beyond this point. The solder's spreading pattern transformed from a square to a circular shape at the beginning of spreading time, gradually becoming irregular as the solder started to wet and spread across the surface of the copper substrate until the end of spreading. Additionally, the larger spreading area of the solder alloy spreading at the end of the spreading time was attributed to the pillar micro-texture on the copper substrate [16]. The molten solder must overcome the energy barriers of the pillars before thoroughly wetting the surface of the copper.

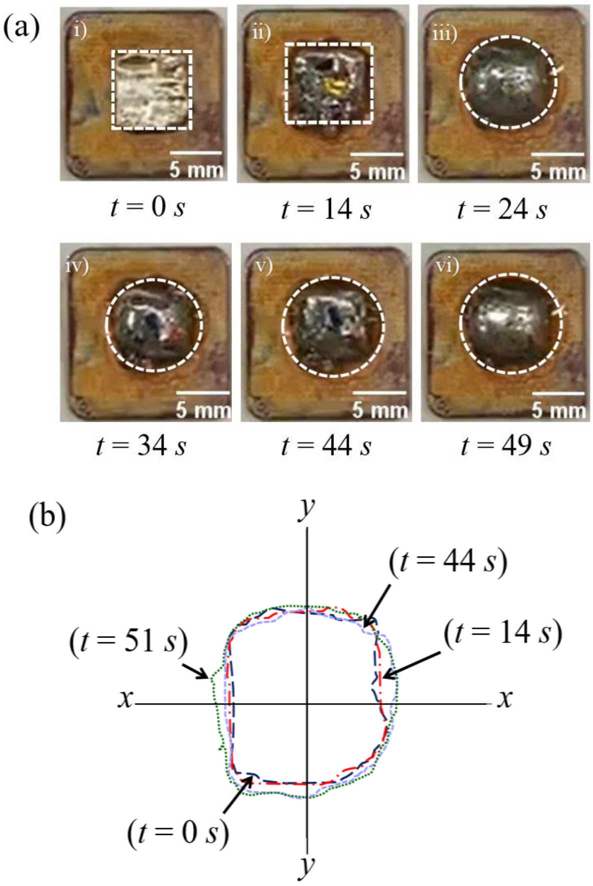

Figure 5. The profile of spreading of Sn-0.7Cu on dimple-textured Cu substrate, (a) images of reflowed Sn-0.7Cu and (b) schematic representation of Sn-0.7Cu spreading.

It was observed that the spread of the solder alloy can be categorised into three stages. During the initial stage, the solder begins to spread rapidly shortly after melting, with the spreading rate demonstrating almost linear progression. The subsequent stage involves the primary spreading of the solder, which is characterized by a slower rate in comparison to the first stage. At this point, the molten solder advances in an almost circular shape. Lastly, in the final stage, the spread area stabilizes, indicating the completion of the spreading process.

The dimple-textured copper substrate exhibited a smaller average spreading area of 60.54 mm^2 compared to the pillar-textured substrate, which measured 66.47 mm^2. During the spreading of molten Sn-0.7Cu solder on the dimple micro-textured copper substrate, the solder flowed and became trapped in the dimples, suggesting a Wenzel state. The high density of dimple texture presented challenges for the solder to flow, requiring it to overcome numerous dimple cavities before further spreading on the substrate. In contrast, the pillar-textured copper substrate exhibits a short period of spreading time, and the retarding force of spreading increases due to overcoming the energy barriers caused by the asperities of the rough surface [16].

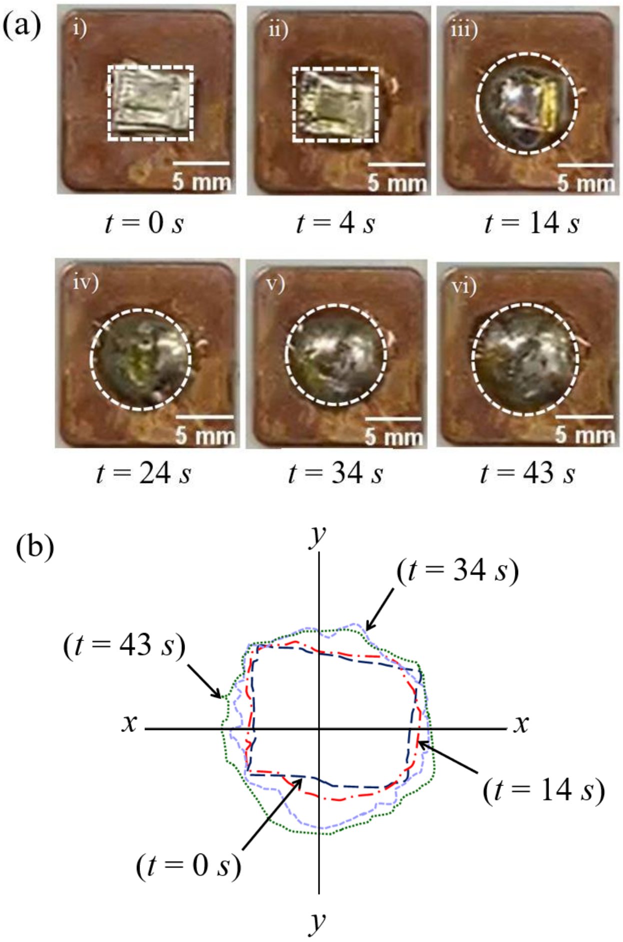

Figure 6. The sequence of spreading of Sn-0.7Cu on pillar-textured Cu substrate, (a) images of reflowed Sn-0.7Cu and (b) schematic representation of Sn-0.7Cu spreading.

Chen et al. [17] noted in previous studies that asperities on rough surfaces act as energy barriers, influencing the ability of liquid to spread. The liquid's capability to overcome these barriers depends on the relative size of the barriers, with a smoother surface facilitating the spreading of molten solder over a wider area. The results were found to agree with Satyanarayan & Prabhu [3], where surface roughness is a crucial factor that affects the wetting of molten solders, and the rough surface has more interfacial area available for spreading the liquid. In another study conducted by Cheng et al. [15] the spreading area of liquid solder is larger with the decrease in substrate roughness. It is known that the substrate's surface roughness plays a role in the wetting behaviour of the solder alloy [4-5].

When considering the soldering process, the spreading area of the solder is a critical factor that is influenced by various elements. Effective control of these factors can result in robust and reliable solder joints with the desired spreading area. The size of the spreading area is important, as it affects the strength and reliability of the resulting solder joint. A larger spreading area indicates greater coverage of the metal surface by the solder, leading to a stronger bond. However, an excessively large spreading area may result in unintended bridging, where the solder forms connections between adjacent metal surfaces. Therefore, carefully considering these factors is essential to achieve optimal solder joint quality.

3.3. The Flow Rate of Sn-0.7Cu

In contrast to the dimple-textured copper substrate, the pillar-textured copper substrate demonstrates a higher flow rate of solder. The solder flow rate on the dimple-textured substrate is approximately 1.44 mm^2/s, while on the pillar-textured substrate, it increases to 1.58 mm^2/s (Figure 7). This difference in flow rates highlights the impact of surface texture on solder behaviour in electronics manufacturing processes. Furthermore, capillary force significantly influences the flow rate of Sn-0.7Cu solder on dimple-textured surfaces. Meanwhile, the pillar micro-texture on the copper substrate acts as an asperity, which poses a challenge for molten solders to flow across the textured surface [17]. Generally, the addition of micro-texture increases the surface area, thereby enhancing the diffusion of copper at the interface. However, this increased diffusion also results in elevated dissolution, which hinders the spread of solder on the micro-textured copper substrate [18]. As a result, molten solder requires more time to traverse the micro-textured surface, leading to a slower flow rate and a reduced area of solder spreading. Wu et al. [16] investigated the influence of surface roughness on the wettability of various wetting systems and found that on rougher surfaces, wetting behaviour exhibited slower spreading kinetics and a longer spreading time.

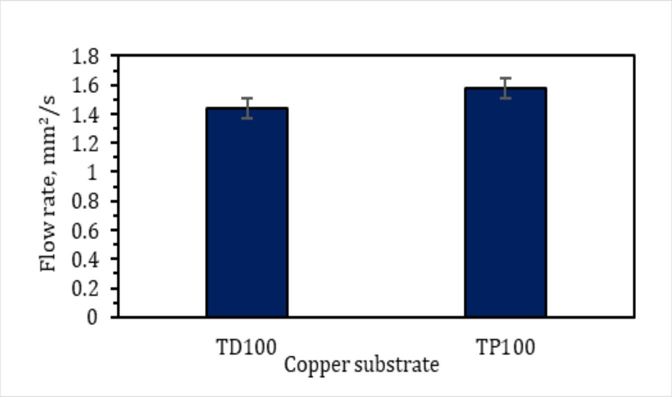

Figure 7. The average solder flow rate on dimple and pillar micro-textured substrate.

4. CONCLUSION

In conclusion, this study explored the influence of micro-textured surfaces on the wetting behaviour of Sn-0.7Cu solder. Specifically, dimple and pillar micro-textures, each featuring a 100 μm diameter, were intricately fabricated using a photolithography technique. The subsequent application of Sn-0.7Cu solder onto these micro-textured copper substrates allowed for an in-depth investigation into key parameters such as spreading time, spreading area, and spreading rate. The findings revealed distinctive wetting characteristics between the two types of micro-textures. On the dimple-textured copper substrate, the Sn-0.7Cu solder showed an extended spreading time of 51 seconds. However, the spreading area and the flow rate are lower, measuring approximately 60.54 mm^2 and 1.43 mm^2/s, respectively. Notably, despite the differences observed, the micro-textured surfaces generally contributed to a reduction in spreading area, indicating an enhancement in solderability. This enhancement is ascribed to the micro-textured substrate's role in facilitating higher copper diffusion during the soldering process. Consequently, the controlled application of micro-textures holds promise for optimising wetting behaviour and solderability in electronic assembly processes, presenting avenues for further exploration and application in the realm of materials science and electronic manufacturing.

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