Wettability and printability of SAC305-xTiO\textsubscript{2} Pb-free solder paste on Cu substrate

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Abstract. This paper was aimed to study on effects of TiO\textsubscript{2} nanoparticles on wettability and printability of SAC305-xTiO\textsubscript{2} Pb-free solder on Cu substrate. TiO\textsubscript{2} nanoparticles at various concentrations (0.00, 0.05, 0.10, 0.50, and 1.00 wt\%) were introduced to SAC305 solder paste by mechanical mixing. Wettability of the solder on Cu substrate was measured in terms of contact angle while printability was calculated from the ratio of printed volume on Cu substrate to ideal volume of solder on the substrate. Results showed that the introduction of TiO\textsubscript{2} nanoparticles decreases the contact angle and 0.33 wt\% TiO\textsubscript{2} is the optimal concentration providing the lowest contact angle within the experimental range. Moreover, the addition of TiO\textsubscript{2} nanoparticles reduced the printability of solder paste on Cu substrate. The higher amount of nanoparticles gave the lower printability. Simultaneous optimization on wettability and printability was also performed to find the optimal TiO\textsubscript{2} concentration.

1. Introduction

In recent decades, environmental problems due to electronics wastes are the major global concern. Many countries issue environmental regulations to control the use of toxic materials in electronics products such as Restriction of Hazardous Substances (RoHS) directive of European Union. This directive has a key impact on electronics equipment manufacturers because it prohibits the use of some hazardous materials in electronics equipment, especially lead (Pb) which is the main component in various customary solders [1-2]. The legislation of RoHS forces the development of Pb-free solders to replace the traditional Pb-bearing solders.

Many Pb-free solders have been developed and commercialized to the market such as Sn-Cu, Sn-Ag, Sn-Ag-Cu (SAC) alloys. Among these new solders, SAC305 (Sn-3.0Ag-0.5Cu) alloy has been widely used in electronics industries because of its good mechanical and electrical properties [3]. However, various properties of Pb-free solders are inferior to the long-established Pb-bearing solders [4-5]. Therefore, research on Pb-free solders is still intensified to improve their properties to level to those of traditional Pb-bearing solders. With the advancement of nanotechnology, many nanoparticles have been introduced to Pb-free solders in order to enhance their properties [6-9]. In case of surface mount technology (SMT), although wettability and printability of solder paste are among the critical characteristics for gaining reliable solder joint, only few articles related to these properties have been reported in the literature [10-15].

This paper investigated effects of TiO\textsubscript{2} nanoparticles on wettability and printability of SAC305-xTiO\textsubscript{2} Pb-free solder paste on Cu substrate. Simultaneous optimization on wettability and printability
was also performed to find optimal concentration of the nanoparticles. Desirability function was used as the optimization tool in this research.

2. Experimental Setup
In this research, SAC305 solder paste was used as the base solder and TiO$_2$ nanoparticles were used as the dispersed phase. TiO$_2$ nanoparticles were mechanically mixed for 30 min with the solder paste for the uniform mixture. A concentration of TiO$_2$ nanoparticles at 0.00, 0.05, 0.10, 0.50, and 1.00 wt% was employed in this experiment. Pure copper sheet with a thickness of 0.35 mm was used as the substrate for wettability test. The wettability test was performed using reflow soldering at 260 °C for 30 s according to IPC/JEDEC: J-STD-020D-01 standard. Wettability of SAC305-xTiO$_2$ on Cu substrate was determined in terms of contact angle. The contact angle ($\theta$) was calculated from equation (1) where H and R is height and radius of the solder joint, respectively [16].

$$\theta = \sin^{-1}\left(\frac{2}{\pi H / R}\right)$$  \hspace{1cm} (1)

Printability of SAC305-xTiO$_2$ was tested based on JIS Z3198-3:2003 standard and it was computed using equation (2) where V is the printed volume on the substrate and $V_o$ is the ideal printed volume of solder on the substrate [17]. MINITAB software was used for optimization of TiO$_2$ concentration via desirability function.

$$\%P = \frac{V}{V_o} \times 100$$  \hspace{1cm} (2)

3. Result and Discussion

3.1 Wettability
Effect of TiO$_2$ nanoparticles on contact angle of SAC305 solder paste on Cu substrate was illustrated in Figure 1. The introduction of TiO$_2$ nanoparticles decreased the contact angle of virgin SAC305 until 0.50 wt% TiO$_2$ and the contact angle was increased again at 1.00 wt%. The decline of contact angle at the beginning was due to the fact that nanoparticles could lower the surface tension of molten solder [18]. However, simultaneously, adding the nanoparticles resulted in increasing of viscosity of the molten solder. Due to these two concurrent phenomena, the contact angle of the solder was therefore decreased to a certain point before upsurge again. Among the five concentrations of TiO$_2$ in this experiment, the concentration of TiO$_2$ nanoparticles at 0.50 wt% gave the lowest contact angle of 9.27°. Therefore, adding the nanoparticles at this concentration provided the best wettability of SAC305 solder paste on Cu substrate. In fact, the degree of wettability can be classified into five levels based on the contact angle as presented in Table 1.

![Figure 1. Contact angle of SAC305-xTiO$_2$.](image-url)


Table 1. Classification of wettability [19, 20].

| Degree of wettability | Contact angle |
|-----------------------|---------------|
| Excellent             | $0^\circ < \theta < 30^\circ$ |
| Good                  | $30^\circ < \theta < 40^\circ$ |
| Fair                  | $30^\circ < \theta < 40^\circ$ |
| Poor                  | $50^\circ < \theta < 70^\circ$ |
| Extremely poor        | $\theta > 70^\circ$ |

From the results, 0.50 wt% TiO$_2$ was the best concentration among the investigated values, however it was difficult to determine the optimal concentration of TiO$_2$ nanoparticles in the experimental range. Desirability function was therefore used to find the optimal concentration. The objective function was to minimize the contact angle of the solder on Cu substrate and the optimization result showed that 0.33 wt% TiO$_2$ nanoparticles provide the minimum contact angle at about 6.18° as presented in Figure 2. Confirmation tests were performed 3 times at 0.33 wt% TiO$_2$ and the measured contact angle was 6.61° ± 0.51°.

3.2 Printability

High printability is always desired in solder printing process for SMT. However, in this experiment, it was obvious that printability of SAC305-$x$TiO$_2$ decreases with the increase of TiO$_2$ nanoparticles as shown in Figure 3. This was due to the fact that the increase of TiO$_2$ nanoparticles provided the higher viscosity of solder paste. With the higher viscosity, the solder paste was more stuck to the stencil’s wall when printed resulting in the lower printability. In practice, the acceptable printability is no less than 80% [21]. As a result, SAC305-1.00TiO$_2$ was not acceptable for solder printing process for SMT while SAC305-0.50TiO$_2$ marginally met the criterion and the best solder paste for printing was the virgin SAC305.

Figure 2. Optimization on contact angle.

Figure 3 Printability of SAC305-$x$TiO$_2$. 

![Printability of SAC305-xTiO2](image-url)
3.3 Optimal TiO$_2$ Concentration for Wettability and Printability

Since the optimal concentration of TiO$_2$ of the wettability and printability was not at the same value, in this section, simultaneous optimization on wettability and printability was therefore performed to find the optimal concentration of TiO$_2$ nanoparticles. Desirability function was used again to obtain the simultaneous optimal concentration. The objective function was to minimize the contact angle and maximize the printability. Using the desirability function, the optimal concentration for both wettability and printability was at about 0.04 wt% TiO$_2$ providing contact angle and printability of about 11.61° and 92.04%, respectively, as illustrated in Figure 4. However, the optimal solution was normally dependent on the selected importance of each response as well as the desired lower and upper limits of each response. Confirmation tests were then performed three times to verify the results and the measured contact angle and printability was 11.05° ± 0.65° and 89.88 ± 5.74 %, respectively.

![Figure 4. Simultaneous optimization on wettability and printability.](image)

4. Conclusion

This paper investigated effects of TiO$_2$ nanoparticles on wettability and printability of SAC305-xTiO$_2$ on Cu substrate. It was found that the addition of 0.33 wt% TiO$_2$ nanoparticles provides the highest wettability and the printability of SAC305-xTiO$_2$ decreases with the increase of TiO$_2$. However, using simultaneous optimization, 0.04 wt% TiO$_2$ was the optimal concentration for both contact angle and printability. The developed solder paste could be used as lead-free nano-composite solder paste in electronics industries. However, in order to be used as composite solder, other properties such as creep and fatigue resistance should be further investigated for this solder.

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