The Effect of Solder Paste Viscosity on Porosity and Mechanical Properties of Surface Mount Solder Joints

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Abstract—This paper reports, for the first time, the results of a systematic experimental investigation of solder paste viscosity on the porosity and mechanical properties of surface mount solder joints. By means of X-ray radiography, it is generally observed that solder joints have greater porosity area fraction for higher solder paste viscosity. With increasing viscosity from 35.3–213 Pa.s, the porosity area fraction varies from 3.0–9.9%, respectively. Thermogravitational analyses on these solder pastes were performed to explain the observed phenomena. It is found that the solder paste with lower viscosity range has a larger evaporation rate of organics than those with higher viscosity range before metal alloys melting, but a smaller rate after metal alloys melting. Shear test results demonstrate that solder joints fabricated with lower viscosity solder paste have higher shear strength by up to 30% (increased from 35.3–46.3 MPa for viscosity change from 213–35.2 Pa.s, respectively).

Index Terms—Organics, porosity, shear strength, surface mount solder joint, thermogravitational analysis (TGA), viscosity.

I. INTRODUCTION

The SOLDER joints are the only mechanical means of attaching surface mount components to the printed circuit board (PCB). Thus, the solder joint integrity and reliability are the most critical issues in surface mount technology (SMT) development. A major type of defects found in surface mount solder joints is porosity. Porosity in the solder joints may potentially cause weakening in joints strength, reduction in electrical and thermal conductivity, and induce fatigue crack initiation [1].

The two most important factors that control the formation of porosity in the solder joints are the relative percentage of organic solvent in the solder paste and the reflow profile [2]. The effects of reflow profile on porosity formation have been studied in our previous work [3]–[5]. The aim of this study is to investigate the effect of the variation of solder paste viscosity on the porosity formation and mechanical properties of surface mount solder joints. The term “organics” is used to describe the materials in the solder paste that are not metallic, such as the flux and oxides that may surround the solder spheres of the solder [6]. The organics include flux, activators, other modifiers, and solvent that dissolves the flux and develops the pasty nature, and finally makes the finished soldering paste more fluid. All this volatile compounds form 35–65% for volume of the solder paste [7]. Thus, a lot of vapor is generated during reflow soldering. Porosity can easily be formed when some of these gases are entrapped between the flat surfaces of printed circuit board (PCB) and component leads upon cooling.

Otherwise, the organics of the solder paste largely determines the solder paste viscosity that governs the flow and deformation behavior of the solder paste, and directly affects the quality of the solder paste deposition on solder pads. Meanwhile, the solder paste viscosity is a time and shear rate dependent parameter. There is no simple mathematical equation that can be used to predict the viscoelastic behavior of solder paste [8]. In practice, the change of the viscosity depends mostly on the change of the organics content in the solder paste. The relationship between the solder paste viscosity and the porosity in the solder joints and its mechanical properties are the subject of this work.

II. EXPERIMENTAL PROCEDURE

SPARKLE PASTE OZ series with 63Sn/37Pb solder alloys and RMA flux was used in this work. Solder paste viscosity was changed by the addition of a thinner provided by the vendor of the SPARKLE PASTE OZ series and appropriate drying. The solder pastes of different viscosity were viewed under a microscope with a magnification of 200× to ensure that the organics was mixed homogeneously. Viscosity measurement was conducted with a Malcom PCU-205 viscometer at 25 °C and 10 revolutions per min after 5 min mixing. After such viscosity measurements, solder pastes of different viscosity were used for stencil printing on a FR-4 PCB that had been cleaned and dried thoroughly by means of a HT-2 screen printer. Then, 1206 leadless ceramic chip carriers were picked and placed onto the pads immediately after the printing and reflowed in the infra-red reflow machine (type: PRECISOLD PS-3000). The temperature profile of the infra-red reflow was as follows:

Preheat — temperature: 100°C
time: 100 s
Reflow — temperature: 230°C
time: 100 s.

X-ray top-view photographs of the solder joints were made with a SOFTEX PRO-TEST 125 X-ray inspection apparatus.
The area fraction of porosity in solder joints can be calculated from

\[ \varepsilon = \sum \frac{A_i}{2S_j} \]  

(1)

where

- \( \varepsilon \) = area fraction of porosity
- \( A_i \) = area of one porosity
- \( S_j \) = termination area of a 1206 LCCC component.

Thermogravitational analysis (TGA) was performed to measure the thermal behavior of the solder pastes under a similar reflow temperature profile.

The shear tests of the solder joints made by the solder pastes of different viscosity were done by means of an INSTRON MINI 44 universal testing system. The schematic diagram of conducting a shear test is shown in Fig. 1. The crosshead of INSTRON MINI 44 universal testing system is made by hardened steel whose stiffness is much larger than that of the solder joints, and hence the deformation can be neglected. This testing system can eliminate the effect of bending and thus ensure a pure shear test. The shear tests were carried out at room temperature and 50% relative humidity, and the crosshead speed was 0.2 mm/min.

III. RESULTS AND DISCUSSION

The microscopic photographs of the solder pads printed with the solder pastes of five different viscosity ranges were taken, and four of them are shown in Fig. 2. Obviously, it is found that when the solder paste has a richer organics content and lower viscosity range, the number density of the solder spheres on the pads is higher. The solder sphere density on the pads is around 4.2, 3.5, 3.3, 3.0, and 2.7 solder spheres per square millimeter with increasing viscosity range from 42.2–238.1 Pa·s, respectively.

The viscosity ranges of the original solder paste sample was from 159.6–169.2 Pa·s. The solder paste with viscosity more than about 240 Pa·s is too thick to be printed whereas that with viscosity less than about 30 Pa·s is too thin for its viscosity to be measured. Therefore, the range of the solder paste viscosity value to be investigated in this study was between 30–238 Pa·s. The specimens were prepared for ten different viscosity values. The porosity area percentage of the solder joints with the solder paste of the same viscosity value does vary in some cases due to the complexity of the solder paste behavior. However, by increasing the sample size, this scatter can be minimized by using the arithmetical mean-value.

Some typical X-ray photographs of the solder joints fabricated with solder pastes at different viscosities are shown in Fig. 3. Fig. 4 shows the average porosity area fraction of the solder joints as a function of the solder paste viscosity. In Fig. 4, it is seen that the porosity area fraction increases with increasing viscosity. With increasing viscosity from 35.2–213.3 Pa·s, the porosity area fraction of the solder joints varies from 3.0–9.9%, respectively. When the solder paste viscosity is less than 49.6 Pa·s or larger than 176.2 Pa·s, this trend is more obvious.

Given that the porosity area percentage of the solder joints in % is \( \varepsilon \) and the viscosity in Pa·s is \( \eta \), the empirical expression for \( \varepsilon \) in Fig. 4 is

\[ \varepsilon = a \eta^2 - b \eta + c \]  

(2)

where

- \( a = 5.0 \times 10^{-6} \) Pa\(^{-3}\)·s\(^{-3}\)
- \( b = 1.8 \times 10^{-3} \) Pa\(^{-2}\)·s\(^{-1}\)
- \( c = 0.223 \) Pa\(^{-1}\)·s\(^{-1}\)
- \( d = 3.345 \)

With the aid of empirical expression (2), the porosity area percentage of solder joints can be predicted for a determinate solder paste viscosity value. In fact, this result is quite unexpected. Originally, it is believed that the organics content of the solder paste is increased upon wetting, and more gaseous vapor should be produced during reflow, thus enhancing the degree of porosity formation. From the experimental results, however, it is observed that the organics in the solder paste can affect the porosity formation not only by the amount of vapor formed but also by the overall physical properties of the solder paste in the reflow process. To study the actual thermal behavior of the solder paste during reflow, TGA was conducted. The temperature program of TGA is similar to the temperature profile of the infra-red reflow, i.e., preheat temperature at 100 \( ^\circ \)C and reflow temperature at 230 \( ^\circ \)C.

The thermogravitational (TG) curves of the ten distinct solder paste viscosity ranges were obtained, and four of them are shown in Fig. 5. It is observed that the solder paste viscosity has no significant effect on the melting temperature of the metal alloy in the solder paste. The metal alloys in the solder pastes with different viscosity ranges all melt at around 183 \( ^\circ \)C. However, the organics weight loss rate of the solder paste with different viscosity ranges is quite different. For the solder paste with the same viscosity range, the organics weight loss rate before and after the melting of the metal alloys is vastly different too.

In Fig. 6, it is observed that the solder pastes with lower viscosity range have higher weight loss rate than those with higher viscosity range in the TG process. The weight loss rate of the solder paste increases with decreasing viscosity range, and the weight loss percentage increases gradually from 3.3
Fig. 2. Microscopic photographs of the solder paste on pads before reflow (magnification = 200×): (a) solder paste with viscosity 42.2–49.9 Pa·s, (b) solder paste with viscosity 94.6–97.6 Pa·s, (c) solder paste with viscosity 130.2–159.6 Pa·s, and (d) solder paste with viscosity 235.5–238.1 Pa·s.

Fig. 3. Typical X-ray photographs of the solder joints: (a) 49.2–49.9 Pa·s, (b) 94.6–94.7 Pa·s, (c) 130.2–159.6 Pa·s, and (d) 235.5–238.1 Pa·s.

for the curve iv to 5.4 for the curve i. It is important to note that the weight loss rate increases with decreasing viscosity range before metal melting (from 1.5 for the curve iv to 3.8 for curve i), but decreases with decreasing viscosity range after metal melting (from 1.6 for the curve iv to 0.7 for curve i). Otherwise, the weight loss rate is much larger before metal melting than after metal melting in curve i, but almost equal in curve iv. This result indicates that the solder paste with a higher organics content (lower viscosity range) has a larger evaporation rate of organics than those with a lower organics content (higher viscosity range) before metal alloys melting, but has a smaller rate after metal alloys melting. For the solder paste with the lower viscosity range, most of the organics are evaporated before metal melting and less vapor remains behind when the metal begins to solidify. The reason is that increasing organics content decreases the solder paste viscosity, thus making the solder paste more fluid such that the metal powders and additives are mixed more homogeneously. This in turn facilitates the escape of evolved gases. Then, the solder joints made by lower viscosity solder paste have lower area fraction.
Fig. 4. The relationship between the porosity area percentage of the solder joints and the solder paste viscosity.

Fig. 5. The diagram of weight loss rate of the solder paste with reflowed temperature profile obtained from TGA. The viscosity range increases from curve i) to curve iv). i) 49.2–49.9 Pa s, ii) 94.6–97.6 Pa s, iii) 130.2–159.6 Pa s, and iv) 235.5–238.1 Pa s.

Fig. 6. The weight loss rate of the solder paste with different viscosity range in TG process: i) 49.2–49.9 Pa s, ii) 94.6–97.6 Pa s, iii) 130.2–159.6 Pa s, and iv) 235.5–238.1 Pa s.

Fig. 7 illustrates the escape of the organic vapor and the formation of the porosity in the solder joints.

Typical shear load-displacement curves of the solder joints are illustrated in Fig. 8. It should be noted that the majority of the curves are fairly reproducible, demonstrating the validity of the test results. Fig. 9 shows the relationship between solder joints shear strength and solder paste viscosity. It is generally seen that the shear strength of the solder joints increase with the decreasing solder paste viscosity. The solder paste viscosity varies from 35.2–213.3 Pa s while the shear strength varies from 46.25–35.27 MPa, respectively, reflecting a significant 30% change. When the solder paste viscosity is below 50 Pa s, this tendency is more prominent. As the solder joints made by the solder paste of lower viscosity have lower porosity area fraction, it has higher ability to withstand shear.

Given that the shear strength of the solder joints in MPa is \( \tau_s \) and the viscosity of the solder paste in Pa s is \( \nu \), the
empirical expression for $\tau_s$ is

$$\tau_s = \frac{A}{v} + B$$  (3)

where

$$A = 3.98 \times 10^2 \text{ M} \cdot \text{Pa}^2 \cdot \text{s}$$
$$B = 3.29 \times 10^2 \text{ MPa}.$$

With the aid of empirical expression (3), the shear strength of the solder paste can be estimated for a determinate solder paste viscosity, and can be conveniently used to predict the shear strength behavior for change in solder paste viscosity.

IV. CONCLUSION

From a systematic experimental investigation of solder paste viscosity on the porosity and mechanical properties of surface mount solder joints, three key findings are summarized as follows.

1) Solder joints have greater porosity area fraction for higher solder paste viscosity. With increasing viscosity from 35.3–213 Pa·s, the porosity area fraction varies from 3.0–9.9%, respectively.

2) From the results of Thermogravitational Analyzes, it is shown that the solder paste with higher organics content (lower viscosity range) has a larger evaporation rate of the organics than those with a lower organic content (higher viscosity range) before metal alloys melting, but has a smaller rate after metal alloys melting. Most organics are evaporated before metal alloys melting, and hence less organics remain after metal alloys melting for the solder paste with lower viscosity range.

3) The shear test results indicate that the solder joints fabricated with higher organics content solder paste have higher shear strength. With decreasing viscosity from 213–35.3 Pa·s, the shear strength of the solder joints increases from 35.3–46.3 MPa, respectively, reflecting an 30% increase of shear strength.

From this work, it is clear that in order to obtain a more reliable and robust solder joint with high shear strength, a solder paste with higher organics content (lower viscosity) should be employed. This provides an useful design yardstick for process...
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engineers who are interested in optimizing the mechanical strength of surface mount solder joints for change in solder paste viscosity resulting from various practical considerations in a real-life process engineering.