

Study of the Rheological Behaviors of Solder Pastes

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Abstract—Solder paste is a homogeneous, stable suspension of solder powder particles suspended in a flux binder, and is one of the most important process materials today in surface mount technology (SMT). By varying the solder particle size, distribution and shape, as well as the other constituent materials, the rheology and printing performance of solder pastes can be controlled. Paste flow behavior is very important in defining the printing performance of any paste. The purpose of this paper is to study the rheological behavior of SAC (Sn-Ag-Cu) solder paste used for surface mount applications in the electronic industry.

The reason why the rheological tests are presented in this paper are two critical sub-processes: aperture filling and paste withdraw. In this paper, we report on the investigation of the rheological profiles, the serrated cone-to-plate system was found as effective in parameter minimizing the wall-slip effect (Fig. 1).

Keywords— rheology, solder paste, thixotropy.

I. INTRODUCTION

The solder paste is used for connecting the terminations of integrated chip with land patterns on the PCB. The paste is applied to the lands by printing the solder paste using a stencil, while other methods like screening and dispersing are also used. A majority of defects in mount assemblies are caused due to the issues in printing process of due to defects in the solder paste. An electronics manufacturer needs to have a good idea about the printing process, specifically the paste characteristics, to avoid reworking costs on the assemblies. Characteristics of the paste, like viscosity and flux levels, need to be monitored periodically by performing in-house tests. One approach currently adopted by the industry is to reduce the solder alloy particle size to facilitate paste flow through the very small stencil apertures.

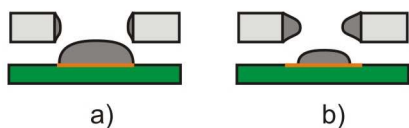


Fig. 1. a) Solder paste is release correctly (no wall-slip effect). b) Solder paste isn't release correctly (wall-slip effect).

However, reducing the particle size in this way has been shown to radically affect the paste rheology and consequently the printing behavior. In this paper we address the need for characterizing 3 solder paste formulations; and present a

procedure for evaluating solder pastes being developed for a application using the stencil printing process.

Current surface mount technology (SMT) methods require the screen printing of a solder paste. This material is a mixture of solder powder, flux and various additives that improve the rheology and other characteristics. In order to print properly, the solder paste must flow easily when sheared, readily pass through the stencil openings, and maintain its shape after printing. A paste characterization method needed to be developed that would predict a paste's stencil performance. It was felt that both the material's viscosity and its inherent yield strength were the significant parameters that should be characterized.

Solder paste is one the most widely used interconnection material in the electrical bond between electronic components and the substrate. Solder paste can be categorized as a homogeneous and dense suspension of solder alloy particles suspended in flux medium. For typical solder paste, the typical metal content is between 88 to 91% by weight, and about 30-70% by volume. The most commonly used lead free solder alloy based SAC. The main constituent of flux medium is a naturally occurring rosin or chemically made rosin. Rosin is used to remove impurities and clean up soldered surfaces and help to solder alloy joint components and metal pads on printed circuit board. A number of different ingredients including solvents, activators, thickeners, thixotropic agent, and tackifiers are added to the flux to provide the desired rheological properties to the solder paste [2].

II. BASIC CONCEPTS OF RHEOLOGICAL PROPERTIES

A. Viscosity

The thixotropy behavior was investigated through rheological test based on shear rate test. In the steady shear rate test, the materials were subjected to a linear rising shear rate from 0 to 32 s⁻¹ for a period 600 seconds. To measure the viscosity of liquids required firstly the definition of the parameters which are involved in the flow. Then one has to find suitable test conditions which allow the measurement of flow properties objectively and reproducibly.

Isaac Newton was the first to find basic law of viscosimetry describing the flow behavior of an ideal liquid. He defined the viscosity η as relation shear stress τ over shear rate D (1) [3].

$$\eta = \frac{\tau}{D} \quad [\text{Pa}\cdot\text{s}] \quad (1)$$

τ - shear stress [Pa]

η – viscosity [Pa.s]

D – Shear rate [s^{-1}]

The parallel cone-to-plate model helps to define both shear stress and shear rate Fig. 2. Cone-to-plate system has been chosen for his best results with solder paste.

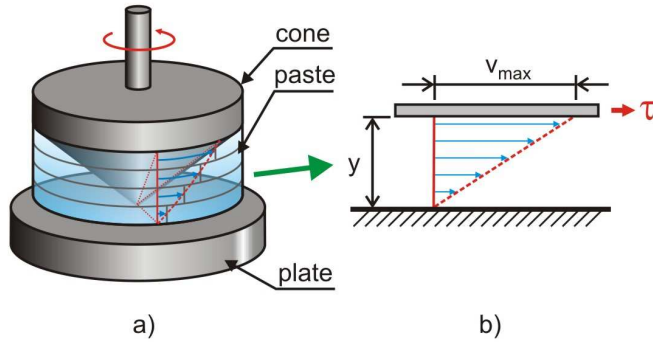


Fig. 2. Principle of cone-to-plate model. a) Cone-to-plate system for measuring solder paste. b) detail for calculation relation of shear stress and shear rate. V_{MAX} is a flow speed, τ is a shear stress, y is gap size.

Shear stress

A force F applied an area being the interface between the upper plate and the liquid underneath leads to a flow in the liquid layer. The velocity of flow that can be maintained for a given force will be controlled by the internal resistance of the liquid, i.e. by its viscosity (2) [3].

$$\tau = \frac{F(\text{force})}{A(\text{area})} = \frac{N(\text{newton})}{m^2} = Pa \text{ (Pascal)} \quad (2)$$

Shear rate

The shear stress τ causes the liquid to flow in a special pattern (Fig. 2 b). A maximum flow speed ' v_{MAX} ' will be found at the upper boundary of plate moved in direction of τ . The speed drops across the gap size ' y ' down to ' $v_{MIN}=0$ ' at the lower boundary contacting the stationary plate. Laminar flow means that infinitesimally thin liquid layers slide on top of each other, similar to cards in a deck-of-cards. One laminar layer is then displaced with respect to the adjacent ones by a fraction of the total displacement encountered in the liquid between both plates.

In the general form the shear rate D is defined by a differential (3) [3]:

$$D = \frac{dv}{dy} \quad [\text{s}^{-1}] \quad (3)$$

In the case of linear speed drop across the gap the differential in the equation above can be approximated by

$$D \approx \frac{V_{MAX}}{y} [\text{s}^{-1}] \quad (4)$$

B. Thixotropy and rheology of solder paste

Thixotropy is defined as: 'Memory' property of a fluid (especially of solder paste) where by its viscosity (resistance to flow) depends on its recent history of flow and not just on the force applied to it. This idea influenced from the Fig. 4.

Rheology is defined as a term describing the viscosity and surface tension properties of solder pastes or adhesives.

Typically viscosity for solder pastes is in range from 10 to 1000 Pa.s. Solder paste exhibits non-Newtonian and thixotropic behavior when subjected to a shearing stress. The viscosity of a material can be defined as the ratio of shear force to shear rate (1). Comparison of flow as well as viscosity for Newtonian and Non-Newtonian liquids implicit from Fig. 3.

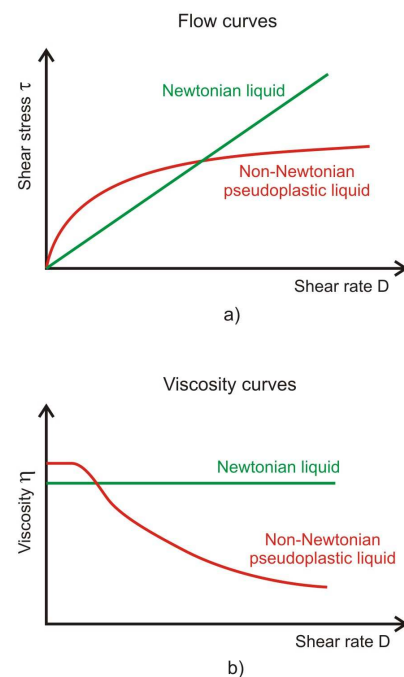


Fig. 3 a) Flow curves: dependency of shear rate stress on shear rate. Curve 1 is Newtonian liquid; curve 2 is Non-Newtonian liquid b) Viscosity curves: Dependency viscosity on shear rate. Curve 1 is Newtonian liquid; curve 2 is Non-Newtonian liquid.

Materials made up of complex organic molecules with a range of organic functional groups are capable of intermolecular interactions that lead to an inherent steady state structure in the material. This phenomenon can also occur as a result of intermolecular interactions between particles, such as solder spheres. For such materials, the thixotropic nature can be shown by a shear rate sweep experiment (for example, in a parallel plate geometry) in which the material is subjected to a shear rate cycle of 0 to 100 per seconds and then 100 to 0 per seconds (called rheogram). The thixotropy is then equal to the area between the ascending and descending shear rate curves. It is indicative of the degree of molecular and solders particle structure in the paste. Diagram describing thixotropy usually named rheogram is in Fig. 4. Other notable features of the rheogram are the initial increase in viscosity, as the as the shear stress increases without significant shear rate increase, followed by the paste 'yielding' and then undergoing shear

thinning. Shear thinning is defined as the property of a fluid (usually solder paste) where the viscosity (that is, the resistance to flow) reduces temporarily as the fluid is subjected to an increased shear force, (for example by a squeegee during the print process). The above behavior is desirable and necessary for satisfactory printing and antislump proprieties. A paste is subjected to a wide range of shear rate during various phases of the printing process (Fig. 5). These are classified as mixing, rolling and stencil printing (Fig. 6) [3].

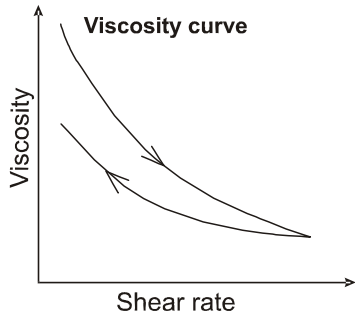


Fig. 4 Diagram describing Thixotropy.

The organic chemicals cream is referred to as ‘flux’ and is generally a trade secret and/or covered by patents. The purpose of flux is to give the solder paste its cream-like texture and to enable formation of metal joints by ensuring that the metal surfaces are ‘clean’ of oxides at the time the metal joint are formed. Rheological behavior of solder paste during stencil printing implicit from the Fig. 6.

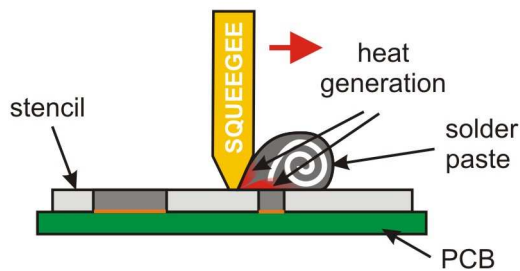


Fig. 5 Stencil printing process. Rubbing squeegee on stencil can produce some heat, and warm up solder pastes.

III. EXPERIMENTAL PROCEDURE

The work report in this work is concerned on rheological characterization of solder pastes designed for pine pitch application to the stencil printing process. The first part of this study deals with solder paste samples rheological characteristics. Two different rheological tests including viscosity sensitivity of temperature and Thixotropy test depend on measuring time duration [1]. We published out only a small part of what we tested within the stencil printing process.

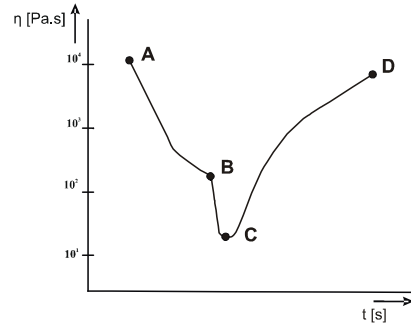


Fig. 6 Viscosity of solder paste during printing process. Point A is beginning of printing process, B is filling up an apertures with solder paste, C is contact point of solder paste and substrate and D is the end of printing process.

A. Solder paste samples

Three commercially available lead-free solder pastes (P1, P2 and P3) were used in the experimental studies report in this paper. All of them are classified as SAC based, no-clean and halide free. All three samples have to same particle size distribution (25-45 μ m) and metal loading 88.5 % by weight. P1 and P2 sample have melting point range at 217-220 $^{\circ}$ C and P3 has melting point range at 217-234 $^{\circ}$ C. The details of these samples are provided in Table 1 [4][5][6].

Table 1. Solder paste properties.

| Paste | Particle size distribution [μ m] | Metal loading [% by weight] | Melting point range [$^{\circ}$ C] | Flux type | Alloy |
|-------|---------------------------------------|-----------------------------|-------------------------------------|-----------|------------------|
| P1 | 25-45 | 88 \pm 0.5 | 217-220 | F1 | 96.5Sn-3Ag-0.5Cu |
| P2 | 25-45 | 88.5 | 217-220 | F2 | 96.5Sn-3Ag-0.5Cu |
| P3 | 25-45 | 88.5 | 217-234 | F3 | 99Sn-0.3Ag-0.7Cu |

B. Rheological Measurements

All rheological measurement were conducted using a HAAKE rotovisco system comprises of sensor system PK100B and measuring system RV20. Principle of measuring cone-to-plate system at this system is in Fig. 2 Special care was taken while loading the solder paste sample onto measuring geometrics. For every measuring were used new sample of solder paste from the container. This step was repeated because solder paste was embossed out from the “between plate area” during repeated measuring or long time measuring. Also we tried to ensure the same conditions of measuring. Before starting the test, the sample was allowed to rest for the period at least 1 minute to allow the sample to relax and to reach a required temperature. Ideal loading procedures were followed for all the tests. Temperatures during the tests were hold at same level from the beginning to the end of test.

IV. RESULT AND DISCUSSION

A. Viscosity test results

Conditions for viscosity tests are in the Table 2.

Table 2 Options of measuring for viscosity test.

| Angle of conic plate [°] | Diameter of cone [mm] | Shear rate [s ⁻¹] | Temperature range [°C] | Time duration [s] |
|--------------------------|-----------------------|-------------------------------|------------------------|-------------------|
| 1 | 20 | 0-30 | 20-30 | 60 |

As show at Fig. 7, all of solder pastes samples have decreasing viscosity when temperature is increase. Highest decreasing of viscosity has sample P3, that's mean this type of solder paste is most sensitive for temperature. Sample P2 has lowest dependability on temperature rising. Viscosity of P2 can be more stable during stencil process, because rubbing squeegee on stencil can produce some heat, and warm up solder pastes (Fig. 5).

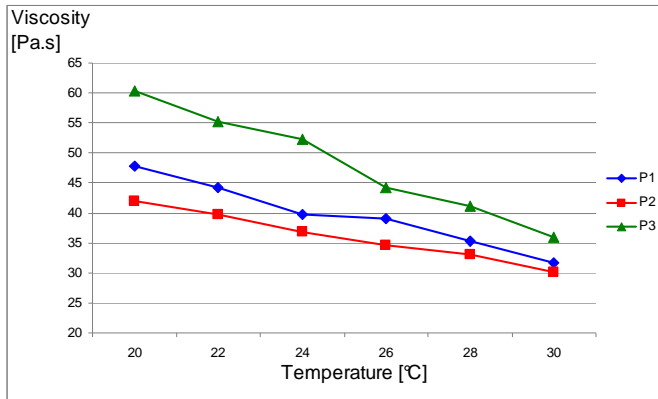


Fig. 7 Viscosity as a function of temperature for different solder paste samples. Shear rate was set up to 30 s⁻¹.

Study of the rheological behaviors of the solder paste helps us better understand behaviors of solder paste in stencil procedure. For our experiment we chose P1 sample. Dependency of rising shear rate on decreasing viscosity is shown in the Fig. 8.

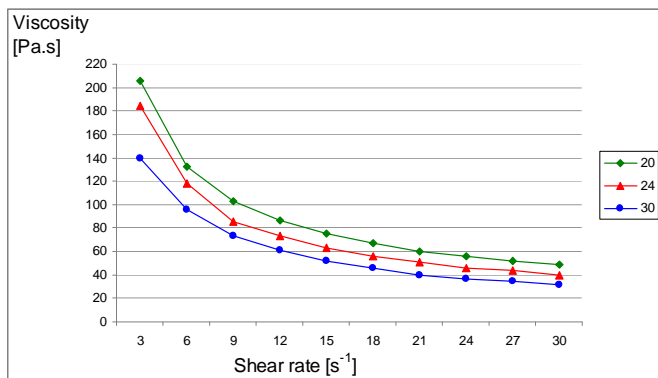


Fig. 8 Viscosity of solder paste sample P1 as a function of shear rate. Set ups of temperature were 20°C, 24°C and 30°C.

We can see were small influence of rising temperature on this effect is more remarkable in Fig. 9. Small shear rate (comparable with stencil printing) decrease has much more effect when temperature decrease. Viscosity decreasing more

than 30 % when temperature rising from 20°C to 30°C at shear rate 3 s⁻¹.

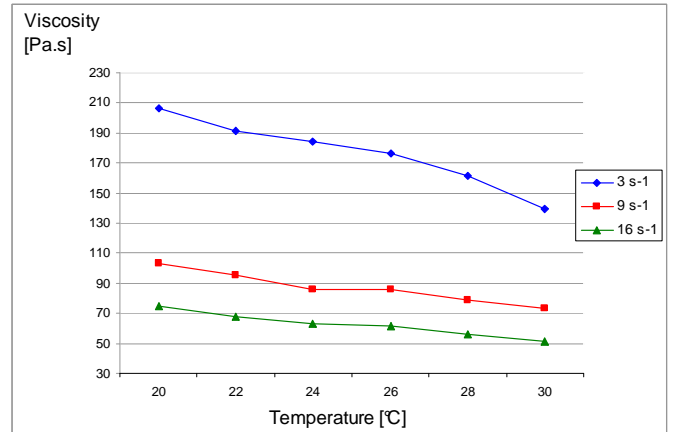


Fig. 9 Viscosity of solder paste sample P1 as a function of temperature. Measured were shear rates 3 s⁻¹, 9 s⁻¹ and 16 s⁻¹.

Fig. 10 shows the flow curves obtained for samples P1, P2 and P3, which show functionality viscosity on shear rate. All samples have decreasing trend during increasing of acceleration of measuring plate rotation. P1 sample has produced the highest maximum viscosity followed by P3 and P2 at low shear rate, but at higher shear rate sample P3 has lowest decreasing of viscosity. The differences in maximum viscosity for the solder paste samples can be attributed to the differences in flux systems. We can predict that solder paste type P3 has lowest dependability on printing speed and it can be more stable than samples P1 and P2.

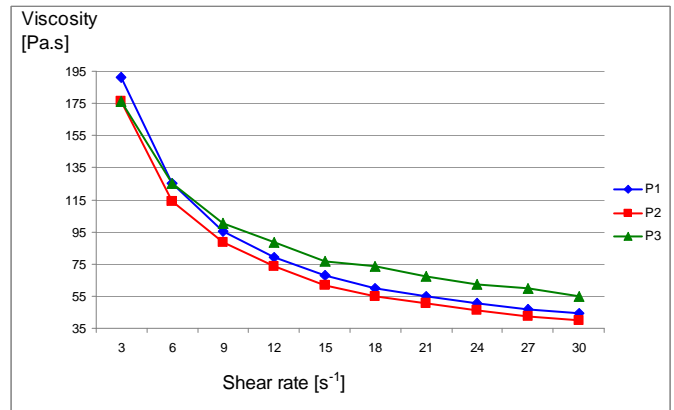


Fig. 10 Viscosity as function of shear rate for different solder paste samples. Temperature was set up to 24°C.

B. Thixotropy test result

Conditions for thixotropy tests are in the Table 3.

Table 3 Option of measuring for thixotropy test.

| Angle of conic plate [°] | Diameter of cone [mm] | Shear rate [s ⁻¹] | Temperature [°C] | Time duration [s] |
|--------------------------|-----------------------|-------------------------------|------------------|-------------------|
| 1 | 20 | 0-30 | 24 | 60 and 600 |

The results from the Thixotropy tests are presented in Fig. 11 at solder paste sample P1. Test shows the resulting viscosities as function of time(60 and 600 seconds). Both

curves have decreasing course, but “600 seconds” curve is lower as expected. Long time shear rate action make solder paste sample easily to flow, that’s mean viscosity of solder paste is depended also on time duration of the shear rate. This experiment confirm of memory properties of solder pate fluid.

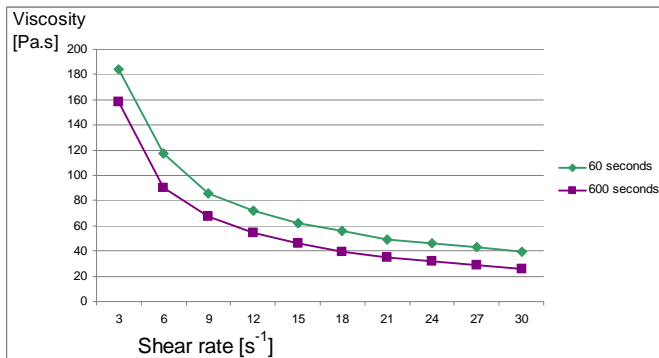


Fig. 11 Thixotropy test at solder paste sample P1. Temperature was set up to 24°C.

V. CONCLUSION

The solder pastes have been reported to be thixotropic, shear-thinning, and to possess a yield stress. The viscosity of solder pastes decrease with increasing temperature as well as with increasing shear rate.

Obtaining accurate rheological measurements on solder paste, help us to obtain the true rheological properties of solder pastes and the difficulties that arose in quantifying the viscometric parameters.

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