A Fast, Precise and Reproducible QC-Rheometry Routine for Solder Paste

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Abstract
SPC data has shown that the solder paste printing process is the primary source of soldering defects in SMT assembly. Consequently, verification of the specified printing properties of solder paste is of paramount importance in the pursuit of higher quality goals, and higher overall yields. Process variations such as temperature fluctuations in the printing area, changing printing speeds and varying stencil life have been recognized as important parameters in the characterization of solder paste, but until today, they never actually have been resolved in a reproducible rheometric methodology.

Moreover, printing developments in recent years, such as the introduction of closed print heads, the apparent diversity in flow behavior of solder paste on electroform versus laser-cut stencils, and specific adhesion to Au-pads, apparently cannot be characterized by the traditional single point viscosity measurement that is still used in many facilities today.

Discrepancies in the flow dynamics of different types of solder pastes used in closed print heads clearly show that the vertical pressure imposed by these systems exerts a major impact on material performance. This phenomenon supports the idea of characterizing the flow properties of solder paste by controlled shear-stress mode methods rather than by traditional controlled shear-rate methods.

This paper describes a rheometric QC-routine for solder paste that takes approximately 16 minutes, and is based on the combination and automation of two different methods. The first method is run in oscillation mode and provides a rheometric characterization of slumping and tackiness. This procedure is automatically followed by a method that is run in rotational mode. The latter provides an index (iv) of shear-rate at different settings of controlled stress. The second index (it) provides viscosity versus different temperature settings, also measured in controlled stress mode. The combined index (ivt) provides a full indication of the printing properties of a solder paste in one single number. In order to ensure compatibility with traditional methods, this routine also provides a single point viscosity determination.

The new QC-routine described herein is a fairly quick and cost-effective testing method that yields precise and reproducible results usable in an SPC program. Moreover, it provides a complete overall picture of the printing properties of solder paste, including its numeric classification regarding slumping, tackiness, its performance at different speeds and its sensitivity to temperature variation.

In An Ideal World

In an SMT process engineer's ideal world, the perfect solder paste, when printing, would have a flow-characteristic as easy as water with no resistance at all. It would flow into any aperture at any process-speed, smoothly and continuously. It would flow until the gentle pressure is released by the squeegee or print head, and would perform perfectly regardless of temperature. It would make no difference whether ambient temperatures would be as low as 18^{o}C (65^{o}F) or as high as 35^{o}C (95^{o}F). That perfect paste would never smear, and instantly after the release of the pressure of the squeegee or print head, the paste deposit on the pad would stand tall and crisp like a skyscraper. It would keep that sharp definition for as long as needed, regardless of ambient temperatures, vibrations or other forces that would attempt to make it slump. Finally, that paste would have a long lasting tack-force until reflow would take place. It would even hold the largest components in place firmly for as long as required.

Of course, this would all be nice, but in an imperfect world, it's hardly realistic. Almost as nice – but far more realistic – is the prospect of being able to certify the flow properties of the solder paste with one single lab-procedure that would put an end to all the confusion and discussions about how to measure such properties in a reproducible and reliable way.

Pre-Requisite: The Rheometer

The printing properties of a solder paste are defined by its rheological properties[1]. In order to characterize the flow of solder paste at different printing speeds, one can express these properties as a rheometric concept, measuring the material with a plate to plate rheometer. Thanks to the availability of more advanced and sensitive electronics, these newer units are able to interpret the torque on the measuring devices with a resolution of 0.01 µm and an angular resolution < 1µrad. Additionally, they control the temperature of a sample more directly through close contact with the heating in the base plate. Temperature control is achieved via a Peltier element, providing a control within 0.1° C. accuracy. The element is also capable of programmable temperature changes within seconds. The temperature can be set at a constant value, or it can vary in intervals or in a continuous ramp as much as 0.8 °C/Sec.

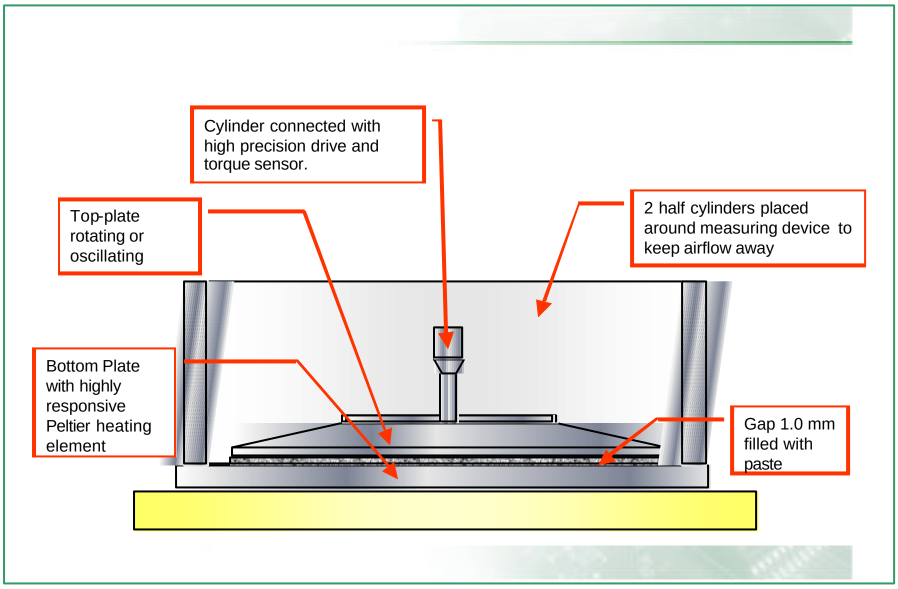

Fig.1 This is a simplified set-up of the measuring device of a plate/plate rheometer as described in this paper. The test sample is between the 2 plates. The bottom plate controls the temperature very accurately. The top-plate rotates or oscillates, depending on the measuring mode. The top plate can also exercise a precisely controlled downward force to assure the same contact force with the test sample even at higher rotational speed.

Additionally, advanced software provides enhanced capabilities for analysis, including smoothing of the raw data, interpolation of data points in a defined range, and calculation of mean values, for ultimately more reliable output.

These systems can also measure in a rotating mode as well as in an oscillating mode. The latter is handy when measuring the slump and tack properties of the paste in a procedure that has been linked to the rotational measurement through an automation feature.

Indexing the Response to Shear Stress (Speed)

When we are interested in the flow speed of a material at a given pressure and when speed (shear-rate) can be measured as the direct output of the test, we find the resistance to flow, (viscosity) to be of secondary importance. In fact, vis cosity is the quotient of shear stress and shear rate.

The index (i_v) that can be calculated to characterize the flow at different print speeds is based on measurements in rotational mode at different settings of controlled shear stress.

As controlled shear stress is the most direct and independently-controlled input parameter in a rheometric experiment, measuring in controlled shear stress mode generally provides more reliable results than measuring in controlled shear-rate mode[1,2,3]. Another important condition is to operate the measurement under a controlled normal force. This option assures that the top plate has the same contact force on the sample at any speed and thus will prevent false readings.

A shear-rate profile is the plot of shear-rate versus shear stress, measured at 25°C. The equation for the i_v-index is as follows:

$$i_v = \log \frac{\dot{g}\,(? = 1250\ \text{Pa})}{\dot{g}\,(? = 500\ \text{Pa})}$$

in which:
i_v = index for flow speed
? = shear stress
$\dot{g}$ = shear rate [reciprocal seconds]

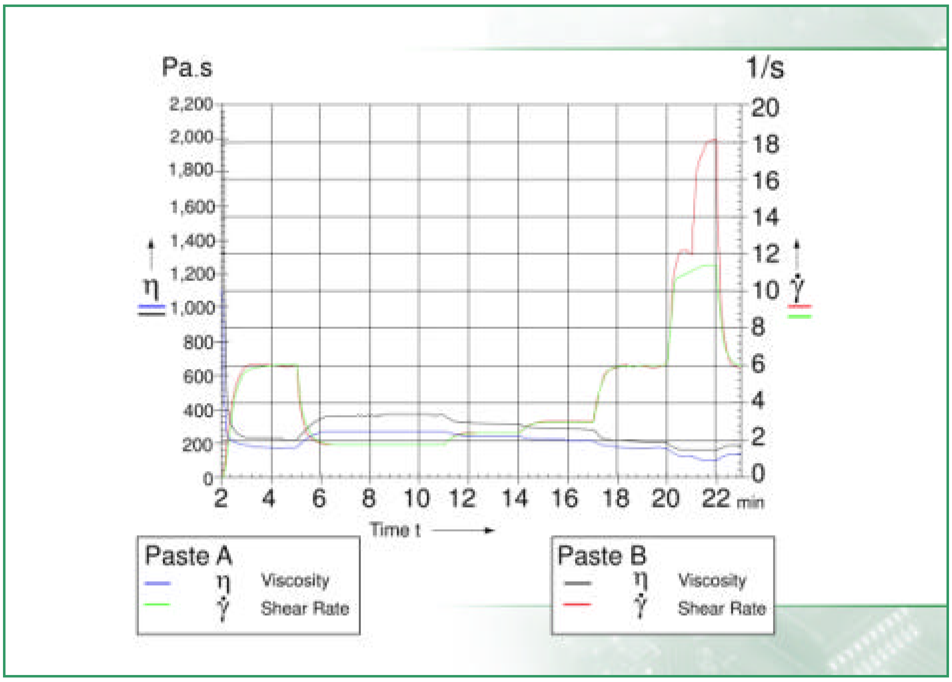

Fig. 2. A shear-rate profile for solder paste, established with a plate/plate rheometer.
The measurement has been made in a stress-controlled mode. Although viscosity values between paste A and B do not seem to be very different, one can observe a significantly higher shear rate for solder paste B (red line) when higher shear stresses are applied.

Characterizing Temperature Sensitivity

A significant number of advanced printing machines available offer climate control, but this option is actually seldom used. Nevertheless, we have noted that temperatures in rooms where printers are operating may vary from below 20° C. on an early winter morning to nearly 30° C. on a hot summer afternoon. In Asia, where air conditioning is a prerequisite to cope with ambient conditions in SMT manufacturing operations, this seems to be less important, but in Europe we know from experience that solder paste must be able to perform without climate control in a great many situations. Therefore, it is interesting to measure viscosity values at different temperatures between 20 and 30^{o} C.

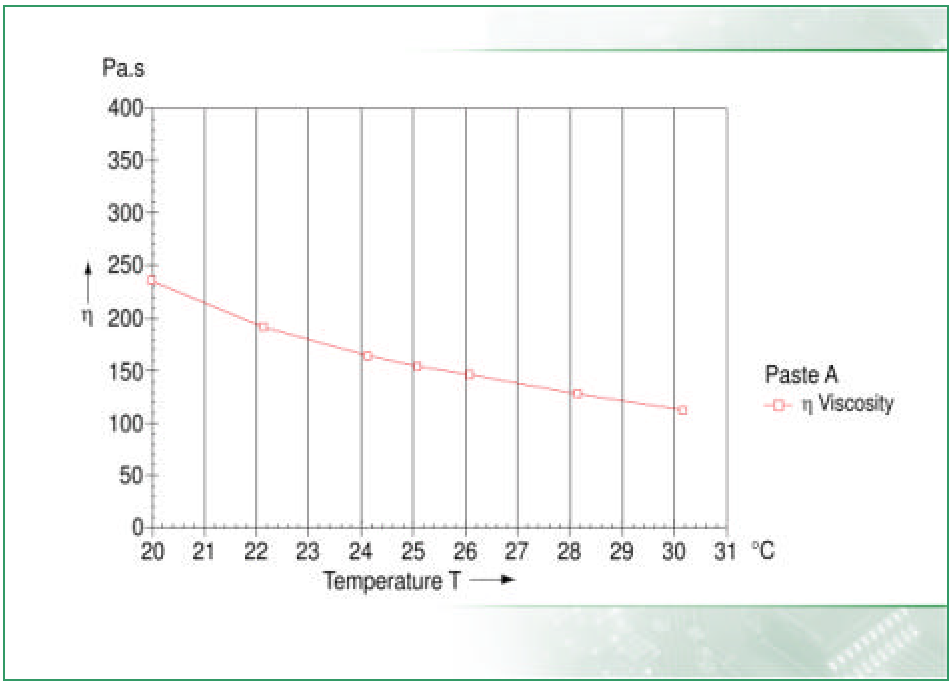

Fig. 3. A temperature – viscosity profile of a solder paste established with a plate/plate rheometer. One can observe a drop in viscosity of over 100 Pa.S when the temperature rises from 20 to 30^{o}C.

In analogy to the index for speed, we have developed an index for temperature sensitivity (i_t). In fact this the plot of viscosity versus temperature. The equation for the i_t-index is as follows:

$$i_t = \log \frac{h\ (t = 20^{o}C)}{h\ (t = 30^{o}C)}$$

in which:
i_t = index for temperature sensitivity
h = viscosity in Pa.S
t = temperature

i_{vt}, The Index for Speed and Temperature Combined

In order to arrive at a single number to characterize the sensitivity of a solder paste for different speeds *and* different temperature conditions, we have combined both indexes into one, i.e., i_{vt}.

A combined index should express the logic that the more responsive a paste is to shear stress and, simultaneously, the less responsive to temperature, the better that paste will perform. Furthermore, the assumption can be made that response to shear stress should be the key element in the index.

For the sake of arriving at a number that can be used at some level of convenience, we have added a constant multiplier to the equation:

$$i_{vt} = \left| \log \frac{\hat{g}\ (? = 1250\ Pa)}{\hat{g}\ (? = 500\ Pa)} \cdot (1 - (\log \frac{h\ (t = 20^{o}C)}{h\ (t = 30^{o}C)} \cdot 0.5)) \right| \cdot K$$

in which:
iv_t = index for speed & temperature
h = viscosity in Pa.S
t = temperature
? = shear stress
$\dot{g}$ = shear rate [reciprocal seconds]
K =Constant (1000)

Paste	A	B	C	D
γ @ τ = 1250 Pa	15.3	16.0	14.0	15.3
γ @ τ = 500 Pa	1.47	1.47	2.00	1.30
i_v	1.02	1.04	0.85	1.01
Change in %	90.4	90.9	85.7	90.2
η @ t =30°C	497	497	503	497
η @ t =20°C	54.6	56.0	90.0	55.0
I_t	0,96	0.95	0.75	0.96
Change in %	89.0	88.7	82.1	88.9
I_{vt}	529.5	545.3	529.3	526.5

Fig.4. This table shows the results of the i_v, i_t and the i_{vt} of four different types of solder paste. Paste B shows the highest i_v, representing the highest response to changes in shear stress. Although Paste C shows the best i_t, indicating the best resistance to temperature changes, Paste B has the best i_{vt}, representing the best universal application.

One Test, 16 Minutes: Rheometric Slump, Tackiness, i_t, i_v and i_{vt}

After the initial development of the i_{vt}, including an R&R test[4] to validate the procedure for its repeatability and reproducibility, we have tested a set of commonly available solder pastes.

The equipment used is a Paar-Physica UDS 200, with a plate of 50 mm diameter, 0^o, and the total test procedure consists of two (2) routines. The first routine covers a rheometric determination of slump and tackiness[1], and it is run at a constant temperature at 25 degrees C. The procedure falls into the category of amplitude sweep testing, which is done in an oscillation mode with a constant frequency of 1Hz. The gap between the two plates is 1.0 mm; the amplitude is programmed in a continuous ramp from 0.1 down to 0.0001 % strain. A number of analysis steps follow the measurement mode; they include steps such as smoothing the raw data, interpolation, and will yield the values for slump and tackiness. This routine is linked to the second through an automation feature. The entire second routine is run in a rotational mode, beginning with a pause intended to give the paste the necessary time for recovery from the shear forces exercised in the preceding oscillation routine. The measurement steps are described in detail in Figure 5.

In a Design of Experiment (DOE), we have measured experimental types of solder paste such as one that, through the addition of a significant ratio of an extremely temperature-sensitive plasticizer, would respond to the smallest change in temperature. The i_{vt} results of this experiment perfectly matched our theory.

Interval		1	2	3	4	5
Measuring Points	#	2	50	50	50	50
	Duration [s]	90	1.5	1.5	1.5	1.5
Interval Duration [s]		180	75	75	75	75
Deflection Angle - ρ [°]		0				
Shear Stress - ? [Pa]			750	500	1250	750
Normal Force FN [N]		0.5	0.5	0.5	0.5	0.5
Temperature - t [C]		20	20	25	25	30

Fig. 5. The settings in the intervals in the measurement mode necessary to calculate the i_t,i_v and i_{vt}. This part of the procedure takes 9 minutes.

Comparing Results

Rheometric values that should provide a quality indicator for printing properties are too often a matter of confusion and frustration to the process engineer. This is mainly because the following issues are quite commonly underestimated, if not entirely ignored:

- The time elapsed between when the measurement(s) are taken and the date and time of production of the paste;
- The history of the paste e.g.: temperature history during transportation and storage, previous usage of the paste;
- Measurement instruments:
  - Different measuring principles;
  - Different modes, settings, and temperature(s);
  - Calibration;
  - Vibrations during measurement;
  - Workmanship (in sample preparation, application).

Conclusion

Statistical analysis in a number of experiments clearly demonstrates that the proposed routine yields significantly more accurate and reproducible results, and also saves time and money. The entire procedure is comparatively brief; it requires approximately 5 minutes for the lab technician to set it up. The rheometer phase requires no more than 16 minutes to produce the final numbers on rheometric slump and tackiness as well as index for speed and temperature sensitivity. All output data is measured, smoothed, interpolated and calculated automatically.

A new industry standard based on indexes such as i_t,i_v, i_{vt} and other rheological parameters including slump and tackiness would finally put an end to confusions and discussions about all kinds of test conditions regarding viscosity. It would also end the hassle with control items such as slump stencils, tackiness probe alignment and other issues. Moreover, this test provides much more useful and reliable information about the printing properties, under varying operating conditions, of a solder paste to the user.

Initially, one might be concerned with the apparent higher initial investment in instrumentation, which also requires a well-trained lab technician to operate and correctly interpret the results. However, many users never measure viscosity and other rheological properties, and rely on certification by the vendor, which may not always be reliable. The abovementioned procedure provides a solid level of assurance to the user.

It is therefore important for the user to demand a certificate of compliance from the paste vendor regarding the testing of viscosity, i_t,i_v, i_{vt} and other rheological parameters such as slump and tack.

In modern business practice, transparency is a key word. Therefore, paste vendors should allow customers to audit their SPC data under certain conditions. This would help take some of the myth and mystery out of solder paste.

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2. *Ein kostengünstiger Methode für Qualitätsicherung.., Ineke van Tiggelen-Aarden, Productronic, October & November 2003*
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