Doc: 0600-00165
Rev 3, 21-Apr-23

Solder Paste Reflow Study

By Stephen Redington

Stephen Redington, PE
U.S. Army DEVCOM Armaments Center
CCDC-ACM-FF, Bldg 1530
Picatinny, NJ 07806-5000

Revisions

REV	Description – Author	Date
1	Initial Rev – Stephen Redington	28-Jan-20
2	Added measured data / revised calculations– Stephen Redington	31-Jan-20
3	Reformatted for public release / Publication	18-Apr-23

Table of Contents

1 Scope ... 4
2 Applicable Documents ... 4
2.1 Association Connecting Electronics Industries (IPC). ... 4
3 Overview ... 4
4 Assumptions and analysis ... 5
5 Experimental measurements ... 8
6 Conclusions ... 12

Table of Figures

Figure 1 Single point solder ball stacking (1 contact between all balls with a common void) ... 6
Figure 2 Mixed Solder ball stacking (1 to 3 contacts between balls with a common void) ... 6
Figure 3 Three point solder ball stacking (3 contact points between all balls with a common void) ... 7
Figure 4 Solder volume prediction formula ... 7
Figure 5 Solder paste sample before reflow. ... 8
Figure 6 Solder paste sample after reflow. ... 9
Figure 7 Resultant solid (side view) ... 9
Figure 8 A rough comparison of volumes ... 10
Figure 9 An exact comparison of volumes (initial and final depths indicated) ... 10
Figure 10 Experimental data and measurements ... 11

1 Scope

This document details the method and results obtained from a study of the volumetric properties of solder paste used in the surface mount assembly of electronic components on a Printed Circuit Board (PCB). Of particular interest is the volume reduction that results from the reflow process in a convection reflow oven used in assembly of a PCB.

2 Applicable Documents

The following documents are applicable in whole or in part. Unless specifically identified, the latest revision available as of the date of this document shall be applied.

2.1 Association Connecting Electronics Industries (IPC).

Title	Document ID	Rev/Issue
Requirements for Soldering Pastes	IPC J-STD-005	

3 Overview

Solder paste is the primary mechanism of attaching electronic components onto a PCB in a Surface Mount Technology (SMT) assembly operation. This paste is commonly available in a number of formulations whereby the grain size of the solder alloy and flux chemistry may vary. In all cases this paste is given a type classification based on the diameter of the grain particles. The coarsest grain would be classified as type 1. Progressively finer grain sizes are given a higher type classification number as per the IPC J-STD-005 specification. Solder paste is comprised of such particles suspended in a flux agent that facilitates the soldering operation. During reflow in a solder reflow oven, this flux is activated and aids in the conversion of the powder into a liquid that coalesces to bond the metal of the component to be soldered to the metal (typically copper) of the PCB. The flux in the paste surrounds this pool of molten solder and protects the surface from oxidation during the reflow operation. It also aids in the removal of oxidation and contaminants from the surfaces to be soldered. This flux residue is often removed in a cleaning operation at the conclusion of the assembly process. Some of this flux may also boil off during the reflow operation. As a result the total volume of solid solder that remains will be a fraction of the original volume that was applied at the beginning of the operation. This study seeks to determine the relationship of the remaining solder alloy volume to the initial paste volume. An analysis is conducted by postulating a number of reasonable assumptions about the physical characteristics of solder paste. The analysis will produce a formula to form a prediction about the resultant solid volume. This prediction will be validated by using the results of an experiment to verify the analysis.

4 Assumptions and analysis

Solder paste is essentially a collection of spherical solder balls of a given diameter. These balls are screened into various particle sizes that correspond to a particular type classification. Each screening operation allows smaller particles to pass through such that the remaining particles are dominated by particles of only one size. It is a reasonable assumption that the relationship of the resultant solid after liquefying the particles would be closely related to the volume of the initial shape. The only deviation of this assumption would be a result of variations of particle sizes within one type classification. A study of IPC J-STD-005 reveals that this deviation is about 30% for type 3 and 4 paste. It is also reasonable to assume a uniform distribution of various particle sizes such that overall larger particles balance out overall smaller particles in the resultant volume.

For analysis, consider the volume of a cube as it relates to the volume of a sphere. To simplify, let's consider the case when the width of a cube is equal to the diameter of the sphere. For the purpose of analysis we will fix the volumes to be studied with a unit width of one. The volume formulas of various solid shapes in terms of width (w) and height (h) are given below.

Cube Volume	V	$=w^3$
Sphere Volume	V	$=(4/3)(\pi(w/2)^3)$
Cylinder Volume	V	$=(\pi(w/2)^2)(h)$
Spherical Cap Volume	V	$=1/3(\pi h^2\ (3(w/2)-h))$

Table 1 Volumetric Formulas for Study

Forgetting about the possible variations of particle sizes within one type classification, it is easy to determine the volume relationship of a unit cube to a unit sphere of the same width by putting a 1 into each formula. This relationship is 1:0.524 or a remaining volume of 52.4% of the original cube. This relationship would hold true for any cubic or cylindrical volume when the solder balls are stacked with single point contact between adjacent balls that form a single void (as shown in Figure 1 below). This packing is very inefficient however. The most efficient packing arrangement is made when the spheres are stacked with a three-point contact between adjacent balls that form a single void (as shown in Figure 3). For the purpose of analysis it is assumed that this packing efficiency is 100%. Since the simple ratio previously calculated assumes a less efficient stacking arrangement, it is reasonable to assume the actual volume remaining after reflow will be higher than 52.4%. The increase in efficiency results from portions of each sphere invading the cube boundary of each sphere. In this case a wedge shaped portion of a spherical cap will fill the space of each corner previously counted as empty. When adding the volumes of spherical caps of the spheres inside the cube boundary it can be shown that this extra volume is roughly 12% to 18% more than the original sphere volume (geometrically derived). Conceptually, the added volume is the volume of two whole spherical caps since each corner of the cube is filled and there are 8 corners in each cube (one wedge in each corner). This results in a residual volume that is closer to 58.6% of the cube. It is reasonable to assume this relationship is accurate for all paste type classifications. This implies that deviations result from how the solder paste actually packs together. These errors would be a result of the following sources:

1) The most efficient geometry for packing uniform spheres is to form a three-point contact between all spheres (e.g. a stack of cannon balls as in Figure 2). This is not exact since the solder particle spheres are suspended in a flux and dispensed at random. A realistic expectation would resemble that of Figure 2 where the stacking is randomly distributed between single point contact and 3 point contact configurations. This produces an efficiency between 88% and 100%.

2) Particles of various sizes may not pack together as expected (i.e. not all spheres will form three point contacts). There will be gaps that result from larger spheres packing next to smaller spheres and some will form single point contacts. This reduces the packing efficiency below 100% by some indeterminate factor.

Least efficient stacking (88% of most efficient stacking)

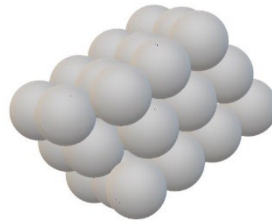
Figure 1 Single point solder ball stacking (1 contact between all balls with a common void)

(Somewhere between 88% and 100% efficient).)

Figure 2 Mixed Solder ball stacking (1 to 3 contacts between balls with a common void)

3) Flux will tend to coat the spheres reducing the ability to pack together tightly. This reduces the packing efficiency below 100% by some indeterminate factor.

4) Some particles may exist that are small enough to pack into the void space formed by the cluster of three balls (i.e. inside the three point contact). This increases the packing efficiency above 100% by some indeterminate factor.



(100% efficient)

Figure 3 Three point solder ball stacking (3 contact points between all balls with a common void)

To correct for these error sources a constant is created, herein termed the packing efficiency. The previous calculations were performed with an assumed packing efficiency of 100%. A more realistic number would be less but greater than 88% (the least efficient stacking). It should be noted that some of the error sources identified above would tend to cancel out over the entire volume of the print. The net effect of all error sources identified and taken as a whole may not be a significant deviation of the 100% packing efficiency estimation. For the purpose of this initial study a reasonable approximation for this constant was determined (guessed) to be closer to 90% vs 100%. This constant is used to adjust the predicted solid volume reduction factor of 58.6% down to an effective reduction factor of 53%. This would be a volumetric loss of 47% from the deposited paste volume. It can be seen that these numbers will have some tolerance associated with them. If we desire a more simplified calculation, we can use an approximation of 50% as the reduction factor. It can be shown this estimation should be accurate to within +/- 15% of the actual reduction and would always result in an excess of solid solder. This puts a safety margin on top of the 3% theoretical error that the simplification causes.

The analytical formula that results from this analysis can be stated as follows:

$$R = G * \varepsilon * V$$

R:	Resultant solid volume
G:	Geometric Reduction factor
ε:	Efficiency constant
V:	Initial volume

Figure 4 Solder volume prediction formula

Where R is the resultant volume; G is the theoretical geometric reduction factor constant; ε is the packing efficiency and V is the starting volume. Since G depends primarily on geometry, this factor is predicted to be relatively constant across differing paste formulas. The efficiency factor would be an experimentally derived constant that would be developed for each paste formula to be utilized. The value of ε can be found by performing the experiment in section 5 below.

5 Experimental measurements

The actual volume reduction factor can be verified by an experiment. These results can be used to validate the analysis and correct the packing efficiency constant used herein. The concept is simple and relies on the following steps.

1) Determine the volume of solder paste in a sample prior to reflow.
2) Reflow the solder paste sample in a reflow oven.
3) Measure the resultant volume.

Although the concept is simple the practical method for obtaining an accurate measurement is a little more involved. The method used to perform this is as follows:

1) Construct a cup of a fixed diameter in a piece of aluminum with a cylindrical volume in the center by using an end mill with a 0.50” diameter. This will produce a void volume with 90 degree corners at the bottom that can be accurately calculated as the volume of a cylinder. This can accurately be determined since the diameter and depth of the void can be measured with a Vernier caliper.
2) Measure the depth of the cup with a Vernier caliper. The diameter can also be measured but can better be determined by measuring the tooling used to mill the aluminum. Calculate the volume as the volume of the cylinder using the diameter and depth of the void.
3) Fill the cup with solder paste level with the top surface. The top can be squeegeed off to form a perfect cylinder of paste.

Figure 5 Solder paste sample before reflow.

4) Reflow the sample in a reflow oven. Since the cup is aluminum the resultant solid will not stick. The cavity will also collect much of the flux residues that result from the normal solder process.

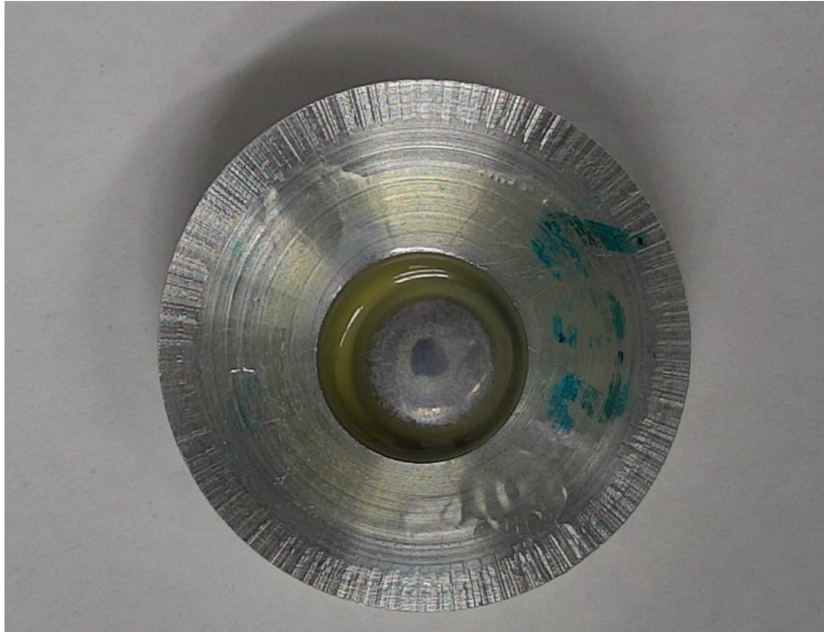


Figure 6 Solder paste sample after reflow.

5) The blob is removed and cleaned. The flux residue can be discarded since we are only interested in the solid solder.

Figure 7 Resultant solid (side view)

6) The resultant solder blob can be pressed into a rough cylinder for comparison however this will result in an error since pressing in open air will produce a shape that is not a perfect cylinder. It will also involve guessing the correct dimeter to press to. This step was skipped in repeated trials.

Figure 8 A rough comparison of volumes

7) The solder blob (Figure 7) is reinserted into the original cup and pressed with a hydraulic press. Enough force is used to cause the solid solder to flow and fill the original cavity. (2 tons was sufficient in this case). The press is used in combination with a ½ diameter punch rod to completely fill the void with a perfect flat topped cylinder of solder.

Figure 9 An exact comparison of volumes (initial and final depths indicated)

8) The new depth of the cavity is measured. The ratio of the depth difference (measured reflow depth) to the original paste depth is the actual reduction factor or percentage volume loss from the original volume.

The results obtained from three trials shown herein tend to validate the analysis. These results are presented in Figure 10 below for three samples measured. The first result analyzed (sample 2) shows a remaining volume of 57%. This is close to the prediction but is discarded herein since the resulting volume deviated greatly from that of a perfect cylinder and the diameter of the solid to the void was only a visual guess. A better method of measuring the resultant volume was developed for the remaining samples. The second and third results (samples 1 and 3) were obtained with a hydraulic pressing of the solder in the original cavity. This makes the final volume a perfect cylinder of the exact same starting diameter. This result can be seen in Figure 9 for sample 1. It should be noted that the depth measurement shown in the figure was later determined to be inaccurate. This was discovered to be due to a tilt of the punch used in the pressing operation. The average height of the samples were updated into the analysis table shown below (Figure 10). The ratio of the initial depth and final depth is a measure of the remaining volume. The prediction from analysis is shown in the table of Figure 10. These results are in close agreement with the theory when the efficiency factor is adjusted to 95% (90% was the initial guess). It should be noted that all the measurements made will contain an error. The scale used to weigh the samples has a precision error of 0.05 grams. Repeated measurements with the Vernier caliper show a deviation of about 5%. The table also shows the result when the 50% rule is used for the prediction. In this case the efficiency factor is ignored in the calculations. When compared to the measured result, the error is about 12%.

Experimental Data (1/14/2020 experiment)

	Initial Cavity Depth (In)	Empty Sample Cup Weight (gm)	Filled Sample Cup Weight (gm)	Solder Paste Weight (gm)	Weight After Reflow (gm)	Weight After Cleaning (gm)	Solder Solid weight (gm)	Flux weight (gm)	Cavity Depth (In) **	Remaining volume (% of Original)	Predicted volume (height)	Prediction Error	Predicted volume (height)	Prediction Error
	Pre Reflow				Post Reflow						Theory		50% Rule	
Sample # 1	0.205	14.85	17.90	3.05	17.80	17.60	2.95	0.10	0.112	54.4%	0.114	2%	0.103	8%
Sample # 2	0.209	15.80	18.65	2.85	18.60	18.35	2.80	0.05	0.119	56.9%	0.116	2%	0.105	4%
Sample # 3	0.164	15.45	17.75	2.30	17.65	17.55	2.20	0.10	0.093	56.7%	0.091	2%	0.082	12%

NOTE: +/- .05 gm Scale accuracy
** Average of two caliper measurements
(shaded) The measurement method was not accurate (see report)
58.6% Theoretical volume after reflow (% of original)
95.0% Approximate efficiency
50.0% Simplified rule of thumb

Figure 10 Experimental data and measurements

6 Conclusions

The actual exact volume reduction cannot be predicted with 100% accuracy as there are several random uncontrollable variables involved. This analysis and experiment shows that the volume reduction can be predicted with reasonable accuracy. This paper demonstrates a prediction accuracy of something better than 5%. It also suggests the simplification rule of 50% of the original volume can be safely used with a 15% allowance for error. These errors result primarily from the geometry and flux of the solder paste particles and how they print.

One lesson learned from this experiment is that small sample volumes are more likely to contain more error than large ones. This is because the measurement errors remain relatively constant as the magnitude of the measurement decreases. Therefore the ratio of error to data increases. More accurate results would be obtained by studying larger volumes. Perhaps a ¾" diameter bore to a depth of 0.250" is an appropriate standard. Careful machining of the sample vessels and punch press will also improve accuracy. The samples used herein were obtained from scrap and hastily machined. They were later found to not be perfectly flat on top. This affected the accuracy of caliper measurements. It also impacted the ability to squeegee the paste perfectly flat to the top surface, as can be seen in Figure 5.

When the measured data was obtained the efficiency parameter was varied to find the value that minimized the distribution of error. It was found that the initial guess was significantly improved by analyzing the data. In essence, this experiment would need to be repeated for each paste formulation to verify the volume reduction and efficiency factors. Repeated experiments using different formulas would likely show the geometrical reduction factor to be relatively constant while the efficiency is likely to be unique for each formula.

It is highly likely that this analysis will hold true for most paste formulas. The method presented herein can be used to validate that assumption by collecting more data on differing paste formulas. If a high degree of accuracy is critical it would be highly recommended to repeat this experiment for the paste formula to be used.