Process Characterization of the 01005 (English) Component Package

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ABSTRACT

An experiment was designed to investigate the process characteristics associated with reflow soldering 01005 component packages. The experiment's objective was to establish the significant process variable causal relationships and was not intended to be a strict statistical treatment of the variables. For solder application, Sn/Pb eutectic solder paste sphere size and solder stencil thickness were selected as independent variables. A systematic, progressive component offset from the nominal placement locations was used to determine process sensitivity to placement variation. The results of the experiment demonstrated the following:

1. Printing a sufficient volume of solder paste and having sufficient paste pad coverage are critical both to the placement process (i.e., successfully achieving and maintaining component location during placement by providing the component with a surface on which to adhere) and for proper solder joint formation.
2. A positional placement accuracy of 0.002 in. is the placement accuracy *neighborhood* needed for low ppm defect rates.
3. A 0.002 in. thick electro-formed stencil provided good results with either type 3 or type 4 paste sphere size.
4. A 0.004 in. thick laser cut stencil provided acceptable results only with paste made with type 4 powder.
5. Rapid heating during reflow is important to prevent solder sphere oxidation.

As found with 0201 components[1], the time/temperature reflow ramp rate emerged as the process parameter with a narrow process window. This result is attributed to the tendency of the small volumes of printed solder paste for 0201 and 01005 components to oxidize more quickly when subjected to elevated oven air temperatures than those printed for larger components. This oxidation interferes with the ability of the Sn/Pb solder spheres to properly melt when the alloy's liquidus temperature is reached on the board. An oven profile that results in a straight, rapid temperature ramp rate of close to 3.0 deg. C per sec. was found to yield good reflow soldering characteristics. These results suggest that reflowing in an inert environment (< 10 ppm O_2) would widen the reflow process window.

INTRODUCTION

The general subject of this paper is electronic product production - specifically, the assembly of the circuit board found in most electronic products, and the use of the nascent 01005 component package in those circuit board assemblies.

For the purposes of this paper the term *manufacturing* will be used to describe individual component fabrication (e.g., threaded fasteners, monolithic chip capacitors, bare circuit boards, etc.). The term *assembly* will refer to the process of putting together individual manufactured parts. The term *production* includes both the *manufacturing* of discrete components, the *assembly* of those parts into subassemblies, as well as the assembly of the completed product.

As with the 0201 component[1], the 01005 package is problematic. It is 25% smaller than the 0201 - a component that already cannot be recognized with the unaided eye.

What are the implications of using this tiny package in a circuit board assembly operation? First, we found the component is being manufactured and is available for discrete resistors and capacitors. At this time, the component package is very expensive (20 – 60 cents U.S. each in medium to low volume). This pricing is thought to be largely supply-and-demand driven and will come down as the demand and, correspondingly, the supply increases. The standard package offering is only available with lead-free terminations (Sn on Ni) and is carried on 8mm paper tape and reel in pockets that are on 0.002 in. pitch (figure 8). There is automated placement equipment available to reliably access the components from the tape and meet the required placement accuracy process window. Static electricity characteristics, especially of the cover tape, are crucial – not to prevent potential electrical damage, but because the components are so light, they could easily be pulled out of the tape pocket as the machine pulls back even a cover tape with a small electrical charge.

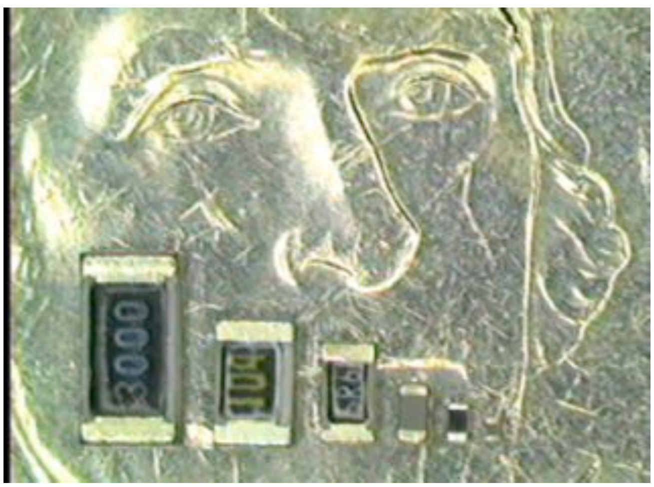
The industry sectors finding the most value in the 01005 component are the RF (high frequency) and hand-held or miniature product markets. These markets find that the performance and size attributes of the components (reducing parasitics by reducing electrical distances and increasing component densities) can outweigh the assembly process challenges they present

THE 01005 PACKAGE

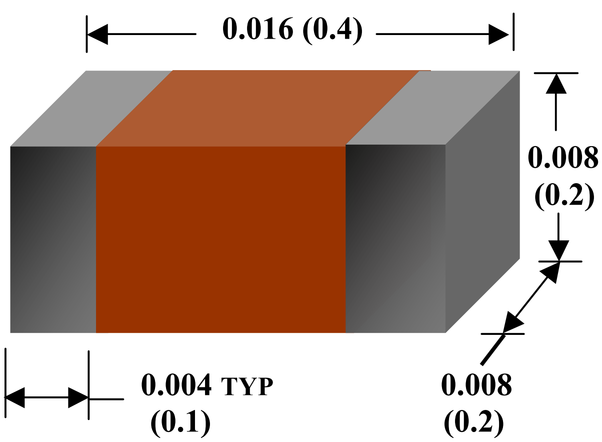
Physical and Mechanical Characteristics

Figure 1 contains a family of passive chip component packages placed on a Jefferson nickel. Figure 2 provides the nominal dimensions for the newest family member, the 01005 package. The dimensions presented are for the chip capacitor used in the experiment. Chip resistors have the same nominal length and width, but are about half as tall. Figure 3 identifies these components, and adds an axial-leaded through-hole resistor, the family patriarch, to the family portrait. Figures 4, 5, 6 and 7 are included to further illustrate the small size of the 01005.

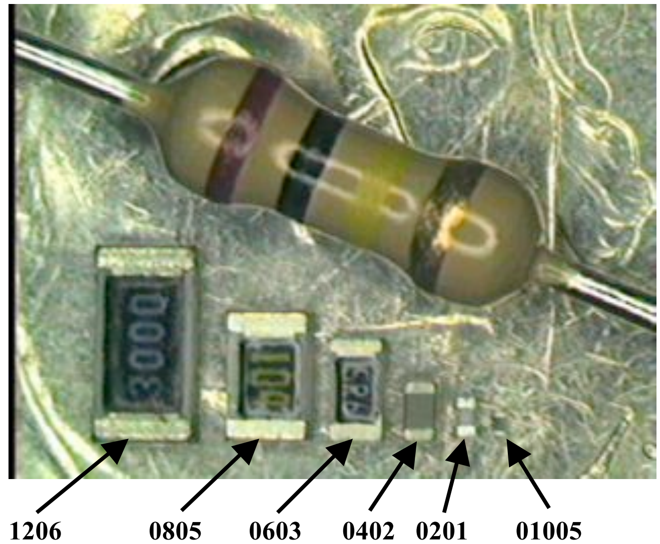
Scaling the weight of an 0201 component that was estimated in reference 1, the 01005 component weighs about 0.114 mg.



Passive Chip Component Family
Figure 1



01005 Chip Capacitor, inches (mm)
Figure 2



Passive Chip Component Family Identified & 1/4 Watt Axial-leaded Resistor Added
Figure 3

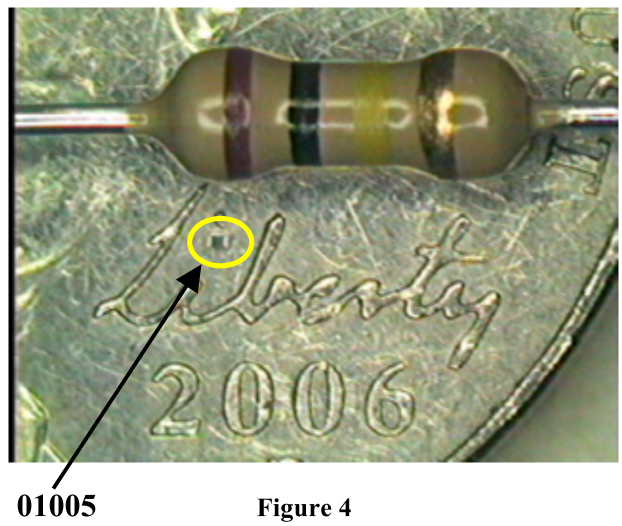


Figure 4

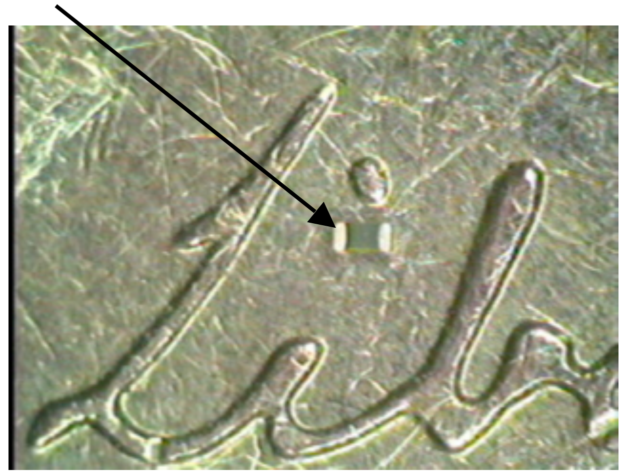
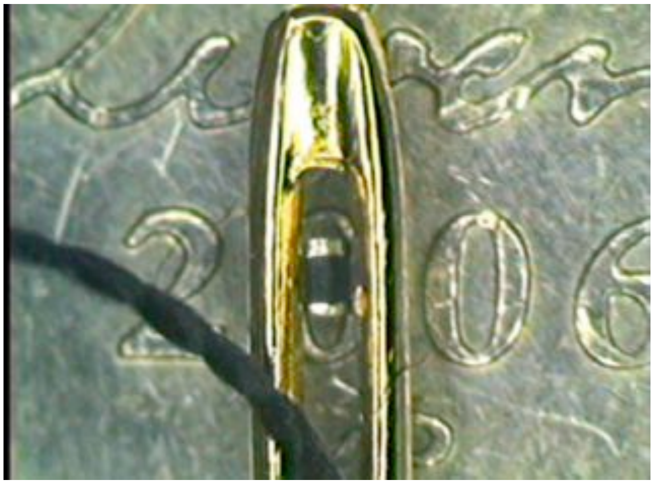
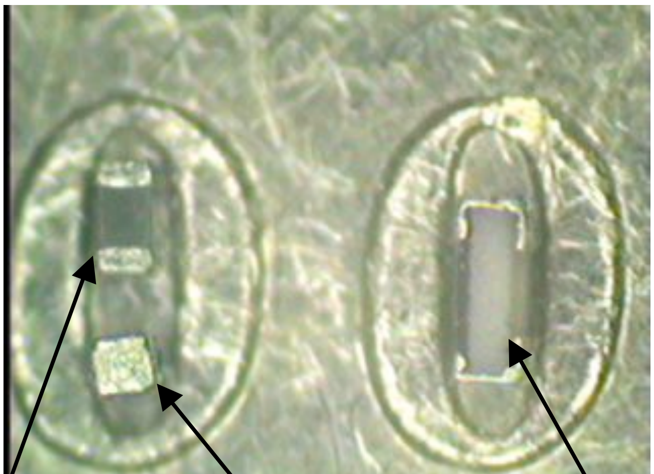


Figure 5



0201 Resistor in the Eye of a Needle
Figure 6



01005 Capacitor **01005 Cap Standing on End**
0201 Resistor on its Side

01005 and 0201 Components in the *2006* Date Marking on a Jefferson Nickel
Figure 7

Generic descriptions of these components are a source of industry confusion. Unless it is already understood, when one refers to an *0402* one must also specify the measurement system. For example, an *0402 English* has a nominal length of 0.040 inches. An *0402 metric or Systeme International (SI)* has a nominal length of 0.4 mm (0.016 inches). The English 0402 is nominally 2.5 times the length of the 0402 metric – clearly, mechanically a much different part. Table 1 summarizes the component family's dimensions for both measurement *languages*. The nominal height dimensions are given for capacitors. As previously mentioned, resistors are thinner than their capacitor package counterparts. It is important to note that the generic descriptions (e.g. 0402) refer to the package's actual dimensions in the metric system (0.4mm x 0.2mm). English dimensional equivalents are converted values (mm divided by 25.4). Therefore, an 01005 English would be more accurately called a 02008 (0.016 in. x 0.008 in.).

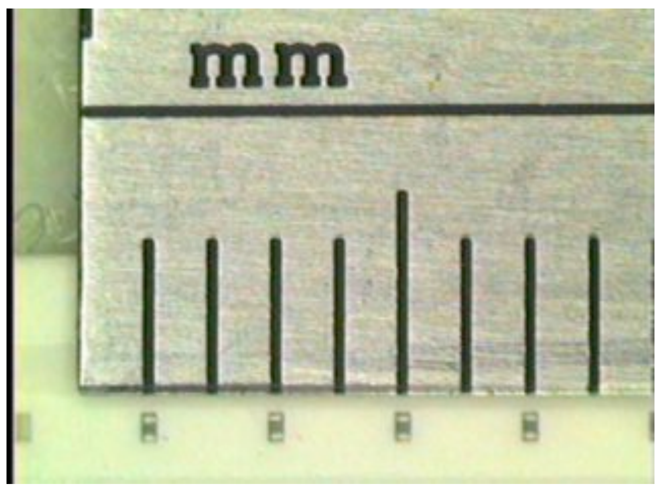
Generic Package Type		Nominal Dimensions for Chip Capacitors as a Function of Package Type					
English	Metric	Length		Width		Height (max)	
		Eng (in)	Met (mm)	Eng (in)	Met (mm)	Eng (in)	Met (mm)
01005	**0402**	.016	**0.4**	.008	**0.2**	.008	**0.2**
0201	**0603**	.024	**0.6**	.012	**0.3**	.012	**0.3**
0402	**1005**	.039	**1.0**	.020	**0.5**	.020	**0.5**
0603	**1608**	.063	**1.6**	.031	**0.8**	.031	**0.8**
0805	**2012**	.079	**2.0**	.047	**1.2**	.047	**1.2**
1206	**3216**	.126	**3.2**	.063	**1.6**	.063	**1.6**

Table 1

Selected Dimensional Tolerances for Capacitors							
English	Metric	Length (mm)		Width (mm)		End Cap Metallization Width (mm)	
		Min	Max	Min	Max	Min	Max
01005	**0402**	**0.38**	**0.42**	**0.18**	**0.22**	**0.07**	**0.14**
0201	**0603**	**0.57**	**0.63**	**0.27**	**0.33**	**na**	**na**
0402	**1005**	**0.90**	**1.10**	**0.40**	**0.60**	**0.10**	**0.30**

na = not available

Table 2

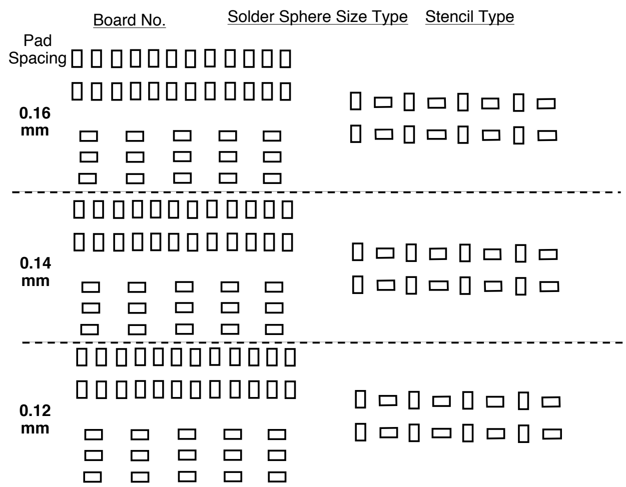


01005 Components on 8mm Tape & Reel with 2mm Pitch Spacing
Figure 8

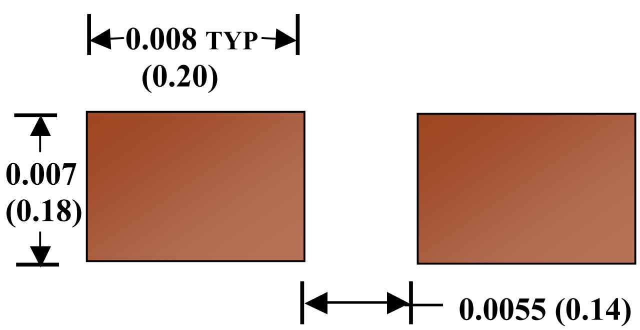
01005 PROCESS CONDITIONS AND RESULTS FOR PRINTING, PLACEMENT AND REFLOW PROCESS STEPS

The Test Board

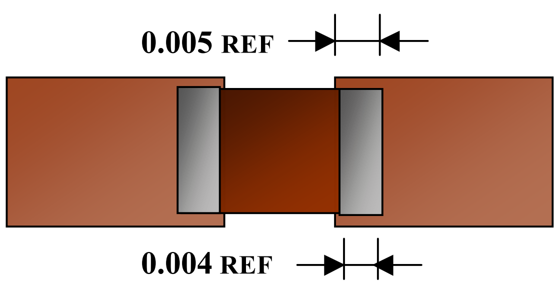
The test board used in the study had copper pads with a high temperature OSP finish. Figure 9 is the generic data sheet that was used for collecting data and illustrates the layout and orientation for the 165, 01005 components per board. The land patterns on the board were clustered in 3 arrays of 55 components - each array having a slightly different pad pitch (i.e., the space between pads for a given component). A typical land pattern with a 0.14 mm pad spacing is shown in Figure 10.



Defect Data Collection Sheet
Figure 9



01005 Pad Geometry with 0.14 mm Pad Spacing, inches, (mm)
Figure 10



01005 Component on Land Pattern with 0.14 mm Pad Spacing, inches
Figure 11

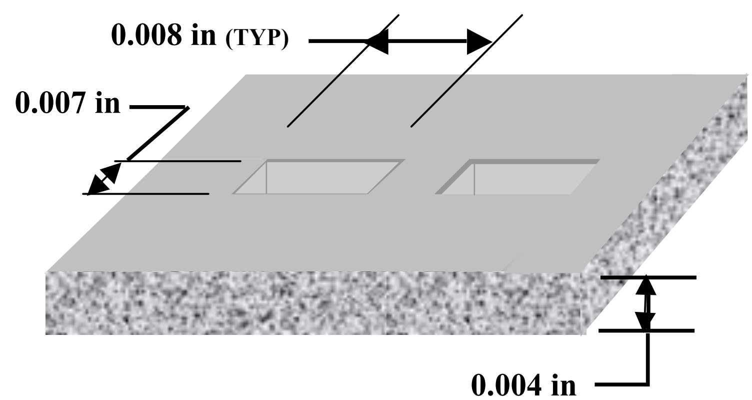
Figure 11 shows the 01005 land pattern (0.14 pad spacing) with a 01005 component ideally placed without offset. Note that any placement offset along the long axis greater than 0.001 in. will place part of one end termination off its pad.

Paste Printing

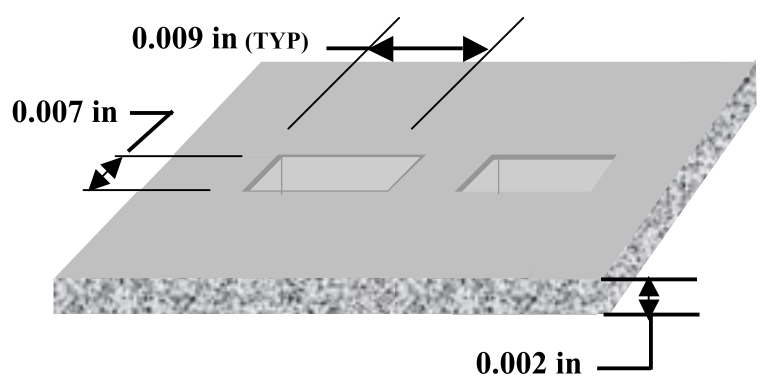
Stencil thickness was one of the experiment's independent variables. Two stencils were designed for the study:

1. 0.004 in. thick laser cut stainless steel foil. (Most agree this is the lower limit for laser cut fabrication, even though foils are available down to 0.001 in thick). Apertures were cut *line-to-line* with the board pad geometries (figure 12).
2. 0.002 in. thick electro-formed nickel stencil. The aperture lengths were opened up by 0.001 inch inboard to get a little more paste deposited without increasing the risk of bridging or solder balling (figure 13).

On-contact printing was done with an automated printer using standard squeegee pressure and print speed.



Laser Cut Stencil Design
Figure 12



Electro-Formed Stencil Design
Figure 13

The Paste

The study used a Sn/Pb eutectic paste with a water soluble flux chemistry. Two sphere size paste formulations (type 3 and type 4) were used as a second independent variable.

Printing Process Results

The 0.002 in. electro-formed stencil provided considerably better printed paste volume and pad coverage because of superior release properties. This was predicted by standard aspect ratio calculations. These ratios are summarized in Table 3.

An aspect ratio (A.R.), between aperture print area (A_a) and aperture wall area (A_w) of greater than 0.6 is generally accepted as the rule of thumb for proper paste release. The other variable found to affect printed paste volume was solder sphere size.

Stencil Thickness	Aspect Ratio, A.R. (A.R. = A_a / A_w)
0.004	0.47
0.002	0.98

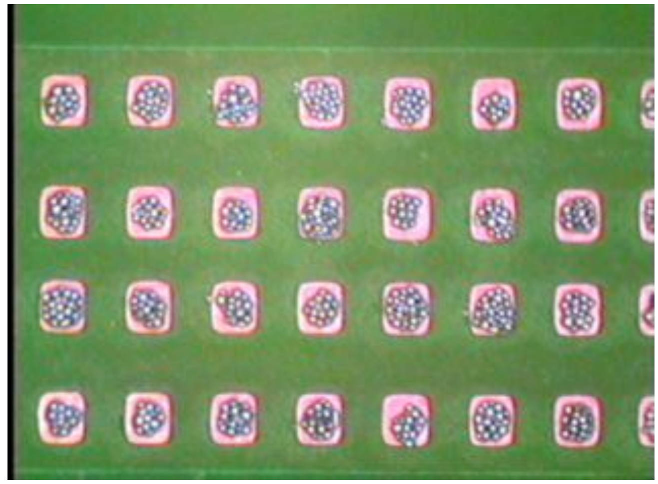
Stencil Aspect Ratios
Table 3

Both stencils deposited both sphere size pastes on the boards. The big difference was paste volume and pad coverage. This can be seen qualitatively in figures 14 & 15. Volume measurements were not made in this study. However, because of the importance of this dependent variable to the results, it is recommended that this metric be part of the quality assurance plan for any assembly operation that is using 0201 or 01005 components. There are two reasons for this:

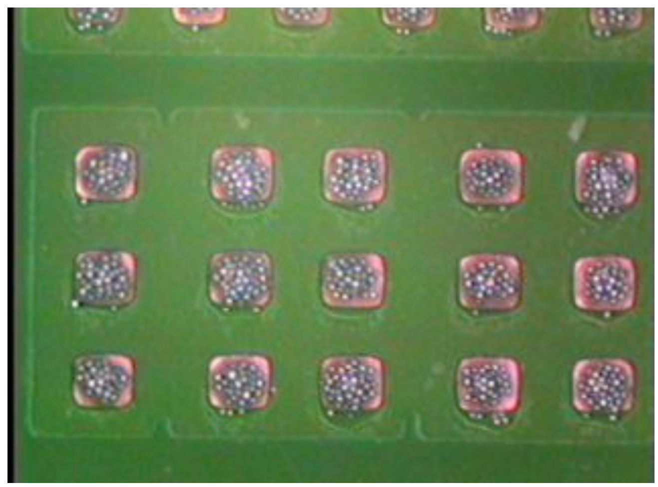
1. The more paste (both volume and pad coverage), the better the chance the component has in staying where the placement machine puts it. Compare the volume and pad coverage of a print on the larger 0402 pads (figure 16) to that on the 01005 pads.
2. The more paste, the more flux and less chance of oven paste oxidation prior to reflow (See reflow process discussion below).

The paste deposits associated with printing through 01005 apertures are so small that the individual spheres can almost be counted. Type 3 spheres have a diameter of 25 – 45 microns (about .001 - .002 in.). Type 4 spheres have a slightly smaller diameter of 20 – 38 microns. Discounting the flux volume (paste % metal content), at best, if Type 3 spheres are packed into an 01005 aperture of the 0.002 in thick stencil, you will get about 50 - 100 spheres on a pad (figure 17). Packing the spheres in the 0.004 in. thick stencil doubles the number of spheres IF the release properties are equivalent. Clearly, they are not.

Sphere size had a significant affect on paste release and hence paste volume and coverage (even more than stencil thickness). The worst case was printing Type 3 paste through the 0.004 in thick stencil (figure 14 & 18). Type 4 paste, even when printed through the 0.004 stencil, gave reasonable paste volumes (figure 15)



Type 3 Paste Printed Through a 0.004 in Thick Stencil
Figure 14



Type 4 Paste Printed Through a 0.004 in. Thick Stencil
Figure 15

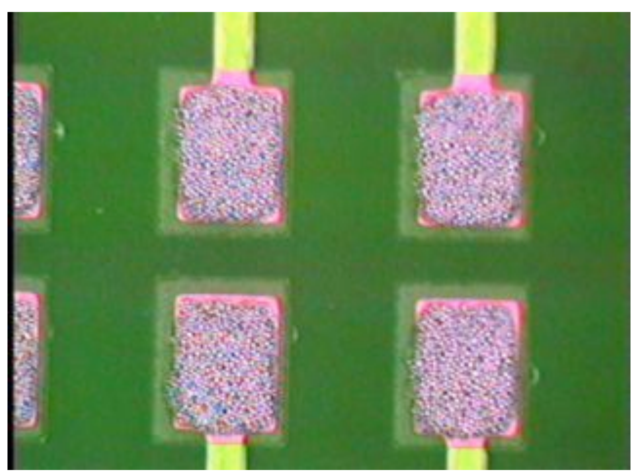
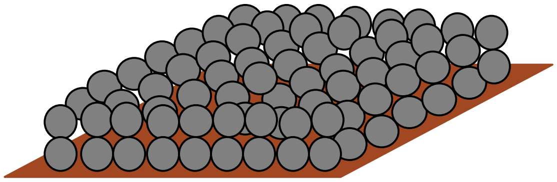


Figure 16
Type 4 Paste Printed Through a 0.004 in. Thick Stencil on 0402 English Pads



Idealized Solder Paste *Brick* Formed by Printing Type 3 Paste with the 0.002 Thick Stencil Used in the Study
Figure 17

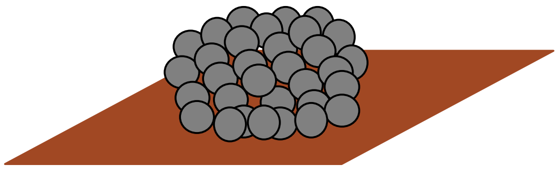
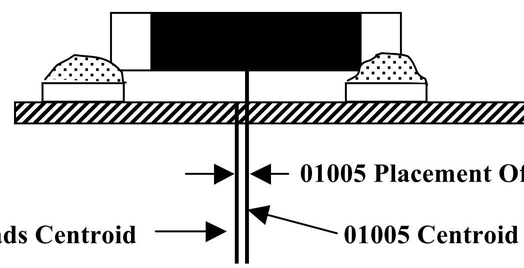


Illustration of Actual Solder Paste Deposited by Printing Type 3 Paste with the .004 Thk Stencil Used in the Study
Figure 18

Component Placement
The 01005 English components were presented to a high-speed placement machine on tape and reel. Parts were accessed and placed at a slightly slower speed than the capability of the machine with normal machine placement pressure. The placement machine had a published positional accuracy of 30 microns (slightly greater than 0.001 in.). Besides placing the parts on their normal pad location, a series of x-axis offsets were introduced via machine programming to establish component sensitivity to placement accuracy (figure 19). The offsets were introduced in 0.001 in. (0.0254 mm) increments out to a maximum of 0.003 in. (0.076 mm).



0.003 in. Offset Placement
Figure 19

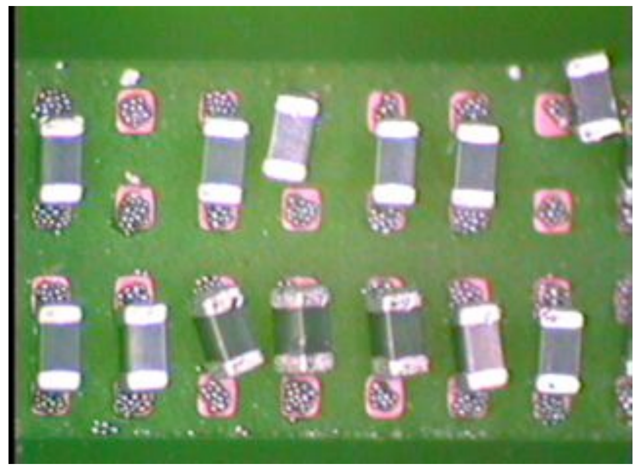
The boards used were designed with some of the 01005 components orientated orthogonally (See figure 9). This afforded the opportunity to introduce an x – offset (long axis) to some of the components and at the same time automatically introduce a y – offset (short axis) to those parts orientated at right angles.

The other placement independent variable was the pitch of the 01005 pads. The board was designed to included pad pitches that resulted in pad spacings of 0.12, 0.14 and 0.16 mm (0.0047, 0.0055, 0.0063 in.). With a maximum x-offset of 0.003 in., a maximum pad space of 0.006, and using the .004 thick stencil, half the termination (0.002 in) on one end will be off the pad. Add to the above condition insufficient printed paste pad coverage, and one 01005 end termination may very well be placed in no solder paste at all. (See Component Placement Results below)

Component Placement Results
The condition described in the above paragraph, or any combination of printing variables that either:

1. did not result in sufficient paste pad coverage, or
2. did not provide enough paste volume to adequately seat the part in the paste on one side of the component or the other,

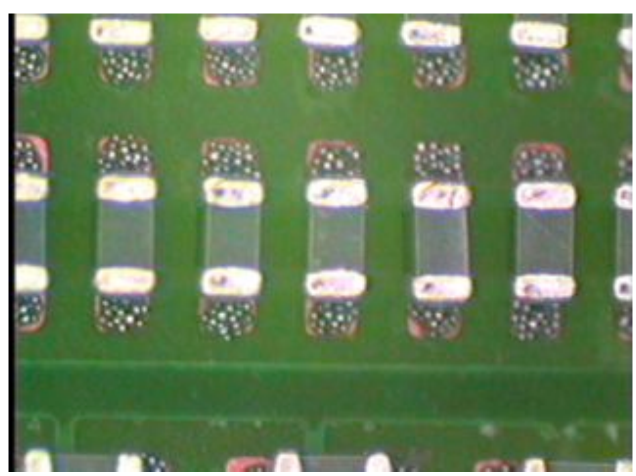
resulted to massive placement defects (figure 20).



Board No. 2 – Massive Placement Defects
Figure 20

To ensure the paste was the root cause of this condition, several runs were done placing 01005 components on double-side tape. This exercise resulted in very little placement variation and very high accuracies. The components were all found to be located on the board where they were programmed to be placed.

When sufficient post-print paste and coverage conditions were present good post-placement results were observed even at 0.002 in. placement offsets (Figure 21).



Board No. 6 – Good Placement
Figure 21

Solder Reflow Process

A 10 heater top – 10 heater bottom, full forced convention in-line oven was used for reflow. Zones were set to result in a time-temperature board heating profile that achieved about a 3 degree centigrade per second, straight-line ramp from room temperature to a peak of 220 degree C. The board was above reflow temperature (183 deg C) for about 45 seconds.

Solder Reflow Process Results

As found in Reference 1, for small deposits of solder paste it is crucial that the paste is quickly heated to its melting point. The small deposits of paste are accompanied by small amounts of flux. The flux does not only prepare the surfaces to be joined, but protects the solder spheres from oxidizing.

As the board is heated in the oven the small amount of flux encapsulating the solder spheres quickly softens and spreads out, exposing the spheres to the elevated oven temperatures. The hot air quickly promotes sphere oxidation, causing each sphere to be enveloped in an oxide shell. These shells prevent the solder from properly melting and result in *cold* solder joints.

Solder defects were of two primary types:

1. Those resulting directly from placement defects (see *Component Placement Results* above).
2. Poor wetting resulting from insufficient reflow that in turn was caused primarily by sphere oxidation or insufficient printed solder.

When printed paste volume and pad coverage conditions were good, reflow results were good (figure 22)

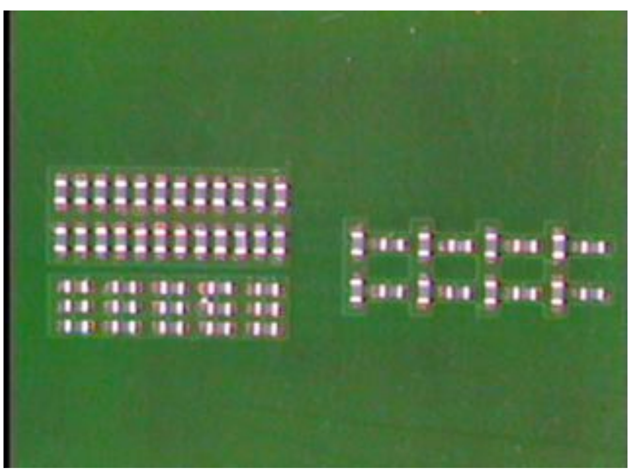


Figure 22
Board No. 14 – Post Reflow

EXPERIMENTAL PROCEDURE

Stencil thickness and solder paste sphere size were selected as the independent variables for paste printing. To determine the component's sensitivity to placement, offsets to the normal placement position were made from 0.001 in. to 0.003 in. in 0.001 step increments. Sixteen boards with 165, 01005 placements per board with different combinations of the independent variables were sequentially run (table 4).

Each board was inspected after each process step and the results were recorded on a defect collection data sheet (figure 9). Each cell on the data sheet represents an 01005 component on the board in its correct orientation and pad pitch.

RESULTS

The results of the experiment are summarized in table 4. Only two defects out of 1320 reflow-soldered components were produced using Type 4 paste, including boards printed with 0.002 and 0.004 in. thick stencils.

Massive placement defectives, and corresponding reflow defects were produced on boards that were printed with Type 3 paste using the 0.004 in thick stencil.

Mixed results were attained when Type 3 paste was printed with the 0.002 in. thick stencil. Acceptable results were received for boards with 0.000 and 0.001 in. placement offsets. At 0.002 and 0.003 in. placement offsets, significant defects were produced.

For a given placement offset, X-offsets (long axis) resulted in more defects than Y-offsets (short axis).

For x-offsets up to 0.002, the pad spacing variation was not strongly coupled to defect rate.

No tombstoning solder defects were observed on any of the sixteen boards.

DISCUSSION OF RESULTS

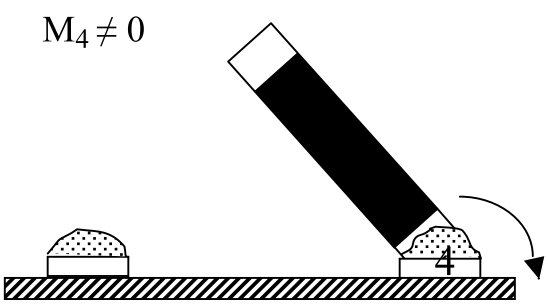
Sufficient solder paste volume and pad coverage were critical success factors. The combination of type 4 paste and a 0.002 in. thick stencil resulted in a paste release characteristic that provided consistently adequate paste volume and coverage.

Based of the results, these conditions when combined with a placement positional accuracy of at least 0.002 in. should produce consistently good results. The machine used in the study had a positional accuracy of 30 microns (slightly greater than 0.001 in.). The machine also demonstrated defect-free, tape-to-nozzle component transfer. No 01005 components were dropped or mis-picked during the population of the 16 boards (1320 components). There were a small number of components that were rejected by the vision system as *not meeting spec*. and were automatically discarded. These machine attributes coupled with good tape and component quality provided reliable 01005 component placement during the study.

It is recommended that, in general, a Gauge R & R be done to ensure the machine meets it's published specifications.

Why no tombstones - especially with components that are as light as 01005s? This question can be answered by conducting a simple force-balance calculation after the solder goes liquidus. The component will move if subjected to an unbalanced force as the solder melts (see figures 24 and 25). To move in the plane parallel to the board, it only takes a net force in the x or y direction (e.g., $F_{wetx} \neq F_{wetx'}$). An unbalanced force such as this can occur if the wetting forces on one component end are different from on the other end – e.g., more paste, or paste in contact with more of the termination on one side of the component. Another way to generate a net force is if the paste melts at different rates on the pads (perhaps more thermal mass on one side caused by a ground plane).

However, for a component to tombstone there must be a net moment (force times distance). Doing a simplified moment balance calculation:



Unbalanced moment causing a component to tombstone
Figure 23

Referring to figure 25, and summing significant moments about point 4:

$$\Sigma M_4 = (F_{wet\ x'})(y') - (F_{wet\ x})(y) + (F_{Buoy})(x) - (F_{Weight})(x) - (F_{Buoy\ Ry2})(x_2 + x_4) - (F_{wet\ y1})(x_1 + x_4) + (F_{Weight\ Ry2})(x_2 + x_4) - (F_{wet\ y2})(x_2 + x_4)$$

As the solder melts and wets up the end terminations of the component, the associated wetting forces (F_{wet}) pull down on each end of the component. If the difference in the x-component of these oblique wetting forces (Xwet & Xwet'), generates a net moment at a point (say, point 4 in Figure 24) that is greater than the opposing moments created by the other forces (e.g., the component weight, other wetting forces under the component, etc.), the component will tombstone. This unbalanced moment is directly proportional to how far up the component this unbalanced force is acting solder. The 01005 is very thin. The moment at point 4 is a function of the distances of the forces to point 4 as well as the forces themselves. So, even though a significant unbalanced wetting force may be present, the distance between this force and point 4 is small. This makes it difficult for a large unbalanced overturning moment to be produced. Therefore, the component may skew in response to the unbalanced forces, but will rarely tombstone.

CONCLUSIONS

The general process window for reflow soldering is considerably narrower for 01005 English components than for 0201 English components[1].

The experiment demonstrated the narrow process window is a consequence of the physical constraints that the 01005 component presents to printing solder paste. It is difficult to reliably print a sufficient volume of solder and cover a sufficient percentage of the pad without the proper combination of stencil and paste. These volume and coverage requirements were found to be necessary to provide a print that can successfully accept a component from the placement machine.

It is recommended that for 01005 component assembly, upper and lower spec limits on paste volume and pad coverage be established. Process capability should be determined before the board assembly process begins, and sample process monitoring should be done to ensure the process stays capable and in control.

The results indicate that using Type 4 solder paste with a 0.002 in. or 0.004 in. thick stencil and placing components with at least a 0.002 in. positional accuracy will yield a capable process (Cpk > 1.33). Paste chemistries that have superior release characteristics are clearly advantageous. A board with both 01005 and components with larger footprints is problematic. The 0.002 or 0.004 in. thick stencil may not provide the paste volume needed for the larger components. For these cases, compromises in stencil thickness, multiple prints with the second stencil having bottom side relief for the first print, and enlarged apertures to overprint paste for the larger components should be explored.

REFERENCES

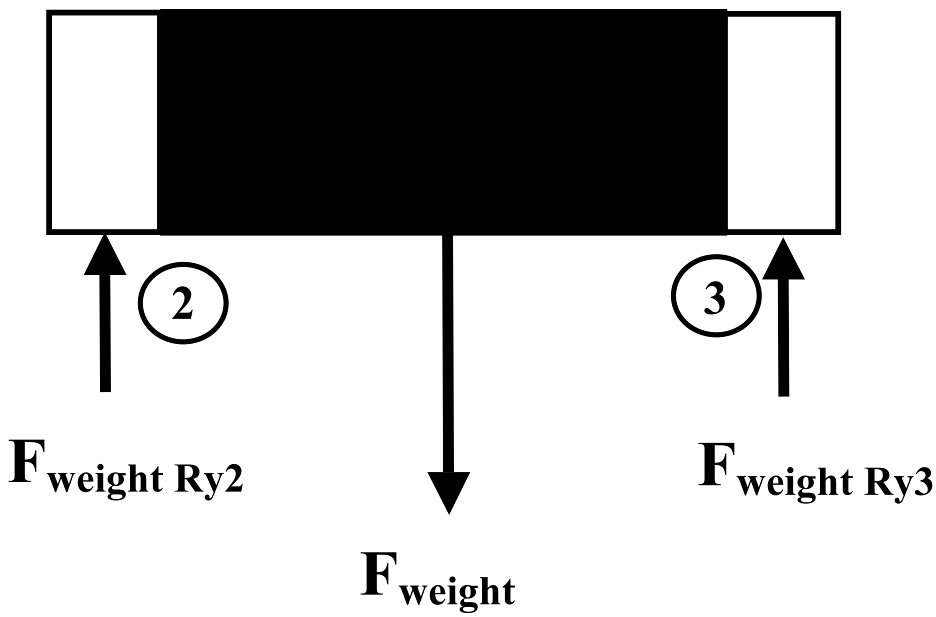
Borkes, T., Fortner, S., Groves, L., "A Statistical Approach to 0201 Component Package Utilization," *Proceedings of SMTA International*, September 22 - 26, 2002, Chicago, Illinois.

Board #	Stencil Thick (in.)		Paste Sphere Size		Placement Offset (in.)				Defects	
	0.004	0.002	Type 3	Type 4	0.000	0.001	0.002	0.003	Place-ment	Reflow
1	x		x		x				10	15
2	x		x			x			Massive	Massive
3	x		x				x		Massive	Massive
4	x		x					x	Massive	Massive
5	x			x	x				0	0
6	x			x		x			0	0
7	x			x			x		0	0
8	x			x				x	1	1
9		x	x		x				0	0
10		x	x			x			0	0
11		x	x				x		18	28
12		x	x					x	Massive	Massive
13		x		x	x				0	0
14		x		x		x			0	0
15		x		x			x		0	0
16		x		x				x	1	1

01005 Process Characterization

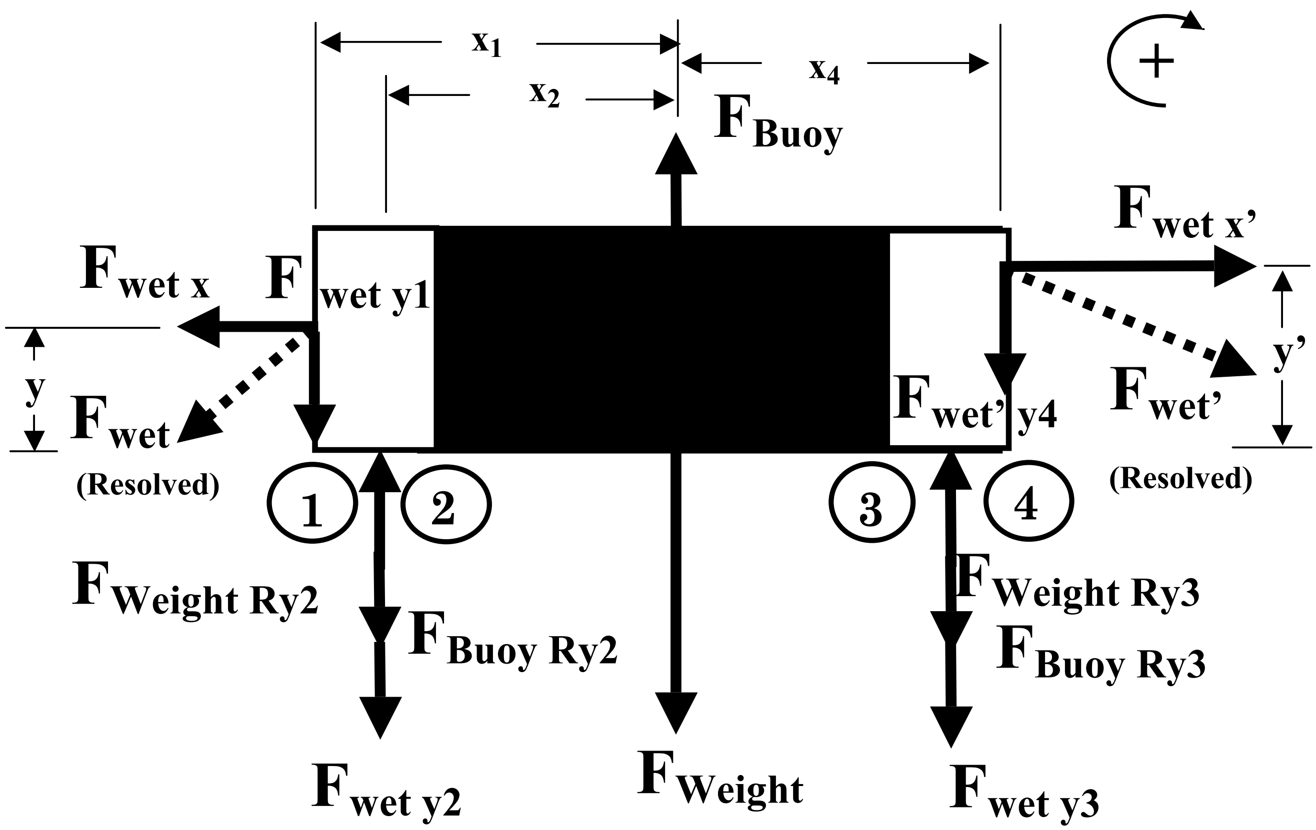
Sample Board Allocation and Defect Results

Table 4



Force Balance Prior to Solder Melt

Figure 23



Some of the Forces Present During Solder Melt

Figure 24