TITLE:

Investigation of the self-centering effect with automatic optical inspection (AOI) for dependable processing of 01005 components

AUTHORS:

Stefan Härter[1], Detlef Beer[2], Jörg Franke[1]

[1]Chair for Factory Automation and Production Systems (FAPS), Friedrich-Alexander-Universität Erlangen-Nuremberg (FAU), Fürther Str. 246b, 90429 Nuremberg, Germany

[2]Viscom AG, Carl-Buderus-Str. 9-15, 30455 Hanover, Germany

Table of contents

1 Introduction and objectives

A substantial driver behind mounting and connection technology for electronic assemblies is miniaturization, with its objective of highly integrated systems. Where passive components are concerned, this miniaturization has led to introduction of the compact size 01005. The size 01005 refers to two-pole components (chip resistors and chip capacitors) with dimensions of about 400 µm x 200 µm which, depending on the manufacturer and component type, have heights of about 120 µm to 300 µm.

Processing these component sizes places considerable demands on the production process as well as the various inspection stages. Despite numerous publications focused on the processing of 01005 components, even now there are no clear-cut recommendations or verified process windows, nor is there a thorough description of potential defect causes. One defect that frequently accompanies 01005 components is the formation of tombstones, in which the two-pole component is raised up by stronger contacting on one side. Typical causes can include insufficient solder paste deposits, displacement during the assembly process, or sub-optimal process control in the final reflow soldering. A reliable and automated inspection of these components to check all essential 3D features presents numerous challenges for the AOI system to be employed.

Within the context of studies supported by statistical analysis, nearly 45000 components were processed in a sample production of electronic assemblies under variation of significant influencing factors. The final AOI inspection was intended to reliably detect tombstone formation, some of which was deliberately arranged. If contacting was successful, the component positions were also measured with high precision so the self-centering effect could be evaluated. "Self-centering effect" describes the floating behavior of the components, which realign themselves using the surface tension of the solder during the reflow process. These studies contribute to improved evaluation of the factors influencing the tombstone effect and the self-centering of size 01005 components.

2 Test description

An FR4 printed circuit board measuring 100 mm x 160 mm was used in the tests (cf. Image 1). The thickness of the test carrier was 0.8 mm and was metallized with a nickel-gold finish. In the left area of the top side of the printed circuit board, two-pole components of sizes 0201, 0402, and 0603 were included in addition to the 01005 components, mainly so effects in the stencil printing process – where different design sizes are expected to be processed – could be evaluated. The recommendations of IPC-7351B provided the basis for the pad dimensional layout [5]. In addition to individual component positions, where the distances between components were analyzed in a gap test, individual land surfaces of the type Solder-Mask-Defined (SMD pads) were also taken into account. The remaining pads were designed with cutouts in the solder resist, or, as Non-Solder-Mask-Defined (NSMD pads).

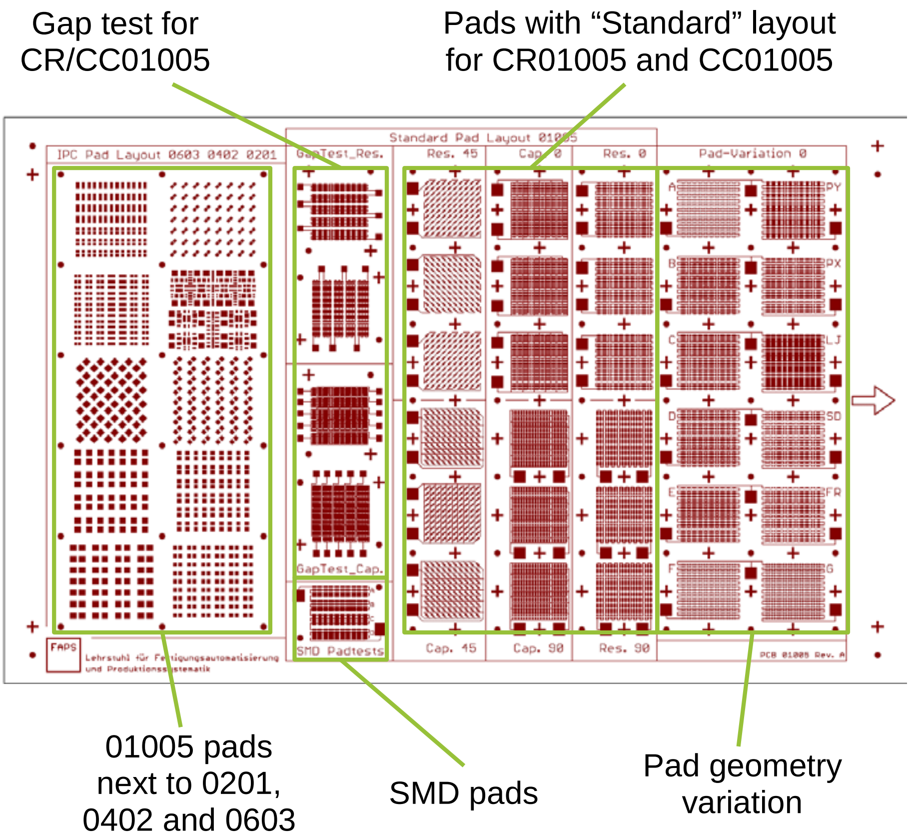
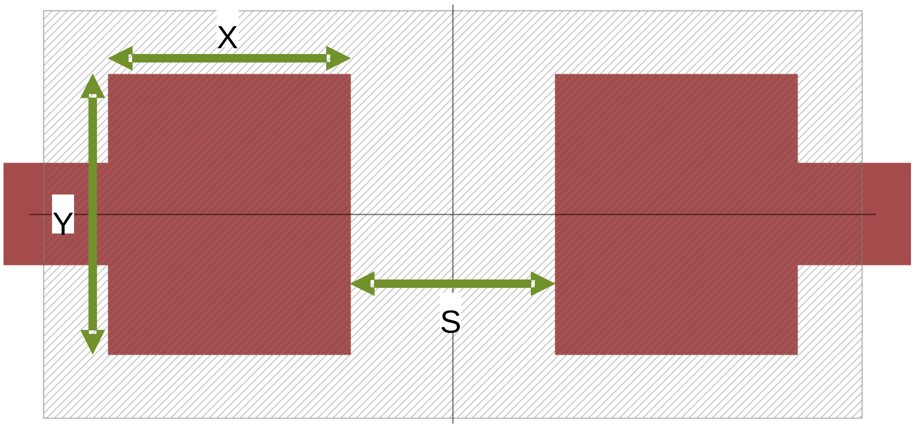


Image 1: The top side of the printed circuit board permitted a number of tests.

On the right side of the printed circuit board, a total of 14 different geometries were considered as the form of the connection surfaces for 01005 components. In designing this board, a standard layout for capacitors and resistors was derived from a number of publications (cf. [3]), as displayed in Image 2. The height variation in the form of the metallization was intended to permit conclusions about the behavior of

01005 components during the processing of pads with different features, whereby the self-centering effect in particular was to be evaluated. The components utilized here had dimensions of about 400 µm long and 200 µm wide; at about 120 µm, the capacitors were about double the height of the resistors. This was taken into account in the connection surfaces of the defined standard layout, which were 20 µm wider in the longitudinal direction of the components.



"Standard" layout	X	Y	S
Resistor CR01005	190 µm	220 µm	160 µm
Capacitor CC01005	210 µm	220 µm	160 µm

Image 2: A standard design for 01005 components was derived from a number of publications in the literature (cf. [3]).

Since some of the surface relationships (aperture opening to aperture wall) of the investigated stencils of 80 µm and 100 µm thickness fell below the recommended value of 0.66, coated NanoWork stainless steel stencils, which have been proven for critical aperture dimensions [8], were used for depositing the solder paste materials. Thinner print stencils were not used because the behavior of 01005 components was to be investigated further on in the project, especially with respect to processing within a heterogeneous range of components. In preliminary tests, first the optimum print parameters for each solder paste were investigated to establish the highest values attainable for transfer efficiency. Solder pastes based on a lead-free tin-silver-copper alloy (SAC305) from two manufacturers were used and two paste types, 4 and 5, were processed. According to [2] [6], a type 4 solder paste has a mass fraction of grain sizes between 20 µm and 38 µm of at least 90 %. In powder type 5, at least 90 % of the mass fraction is distributed between grain size diameters of 15 µm to 25 µm.

Solder paste supplier, paste grain and stencil thickness were varied in two stages apiece during the stencil printing process. Four assembly positions, which were differentiated into reference placement, placement with displacement of 50 µm in the x- and 100 µm in the y-direction, and with 30° rotation, were considered in the subsequent assembly process (cf. Image 3). 50 resistors and 50 capacitors were assembled onto each of the 14 varied metallization layouts and soldered under a nitrogen atmosphere in the concluding reflow process. This resulted in a test plan comprising 32 printed circuit boards with a total of 44800 components.

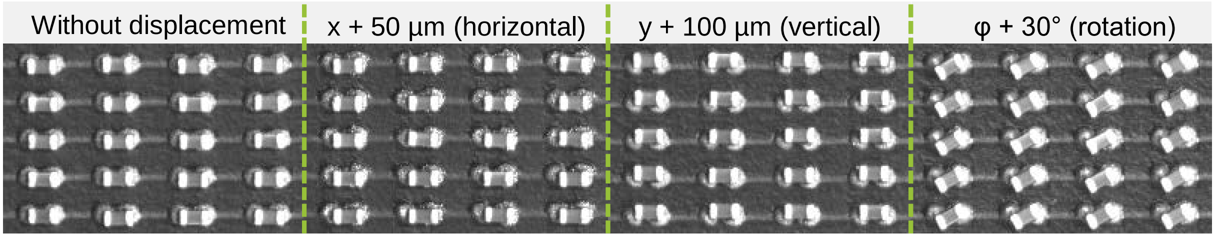


Image 3: Four positions were considered in the assembly with 01005 components (depiction of the reflow soldering process as example).

The test series was conducted under constant climate conditions in a networked SMD production line. After the paste print process, the components were assembled according to the Collect & Place principle with full assembly performance, whereby the placer head used had a placement accuracy of ± 41 µm (3σ) or ± 0.5° (3σ). Prior to the start of the test series, the pick & place machine was calibrated to exclude systemic displacement to the greatest degree possible. The respective manufacturer recommendations for the solder pastes used were taken into account during profiling of the temperature-time course, so the best possible process control could be accomplished. After production of the electronic assemblies, the components were inspected and measured by an automatic optical inspection.

3 Automatic optical inspection of 01005 components

3.1 The inspection system and the inspection coverage

The AOI measurement of the 01005 components was performed by the S3088 *ultra* system from Viscom AG (Image 4). This inspection system is distinguished especially by its XM camera technology, and with its standard 8 µm resolution is ideally qualified for this measurement task. One inspection sequence was defined for each of the component types CR01005 and CC01005 and was held constant for all pad and test variants to ensure the results could be compared. Along with the actual measurement task, the traditional AOI inspection stages such as component presence, solder joint quality and tombstone formation were covered. Defect detection was assured by use of the proven "Integrated Verification".

Image 4: The AOI system S3088 ultra from Viscom AG was employed for measurement of the 01005 components.

That the special features of the test plan gave rise to a great many tombstones quickly became apparent during inspection program generation (cf. Image 5). To maintain the integrity of the measurement values, the inspection sequence comprised the following:

- Stage 1: Inspection for component presence and tombstone formation.
- Stage 2: Measurement of the x-, y- and φ-position of the component (rotation away from horizontal). There was only one valid measurement value when just the first inspection stage was completed with no defects.
- Stage 3: Inspecting the solder joint quality.

Evaluation of the test results proved that missing components and defective solder joints occurred only marginally and so could be dismissed. In contrast, the occurrence of tombstones was a valuable indicator for test evaluation and analysis.

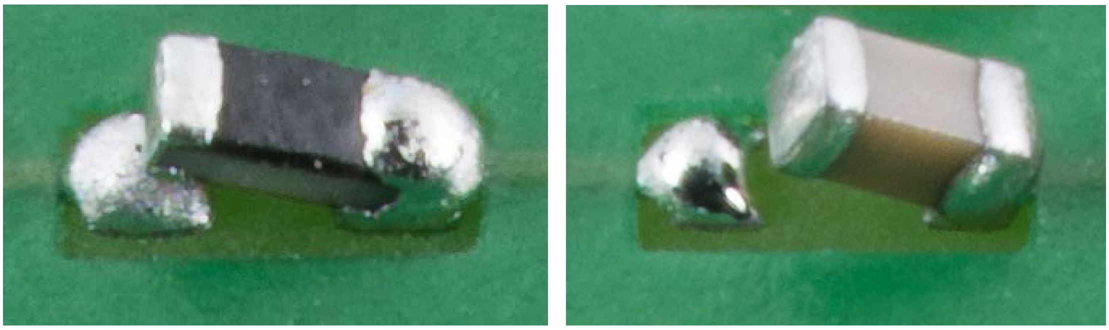


Image 5: Exemplary tombstone formation on a CR01005 (left) and a CC01005 (right)

3.2 Special features of component type C01005

During processing, one other particular challenge arose with component type CR01005; specifically, the component had a height of only about 120 µm. With the pad layout used and a circumferential stencil reduction of 10 µm, the solder deposit was usually too large (cf. Image 6).

Image 6: The solder joints display the relatively high solder deposit for resistors (left) and in a typical cross-section (right).

This effect was even more pronounced with the 100 µm stencil. Normally the solder flows away over the face surface of the terminal connection and spreads out at the component cap. By comparison, due to their greater height, the CC01005 components were unremarkable where paste quantity and solder joint characteristics were concerned (cf. Image 7).

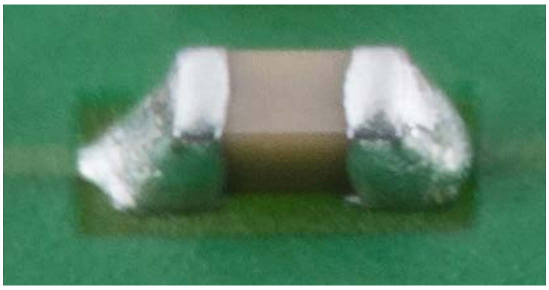


Image 7: The solder quantity for the CC01005 components is comparatively unremarkable.

The two images shown in Image 6 clarify the excessive solder with resistors once again. An IPC-compliant ideal solder joint cannot be achieved in this manner; this was taken into account when creating the inspection program. A quandary emerged here. On the one hand, the surface area of the solder deposit for the CR01005 components could be reduced; on the other, the smaller the aperture openings became, the more of a challenge they posed for the paste print process. The standard area ratio value of 0.66 was already fallen below with the 80 µm stencil (cf. exemplary values for the defined standard layout in Image 8).

Component	Aperture width	Aperture length	Aspect ratio 80 µm stencil threshold 1.5	Aspect ratio 100 µm stencil threshold 1.5	Area ratio 80 µm stencil threshold 0.66	Area ratio 100 µm stencil threshold 0.66
CC01005	200	210	2.500	2.000	0.6402	0.5122
CR01005	180	210	2.250	1.800	0.6058	0.4846

Image 8: Some of the area ratios fell below the value of 0.66 recommended by IPC.

3.3 Formulating the measurement task

Before the actual measurement task could be started, the stability and the measurement capability of the AOI and the inspection program together had to be examined. A procedure working in the subpixel range of the 8 µm camera resolution was employed in examining the measurement values. By combining edge and component center of mass information, resolutions in the 500 nm range could be achieved. To verify reproducibility, 50 CR01005 and 50 CC01005 components were inspected 100 times consecutively and the results compiled in a sigma distribution chart (cf. Image 9). The AOI delivered a sigma of < 3.05 µm, and so was declared to be capable of undertaking the displacement measurement.

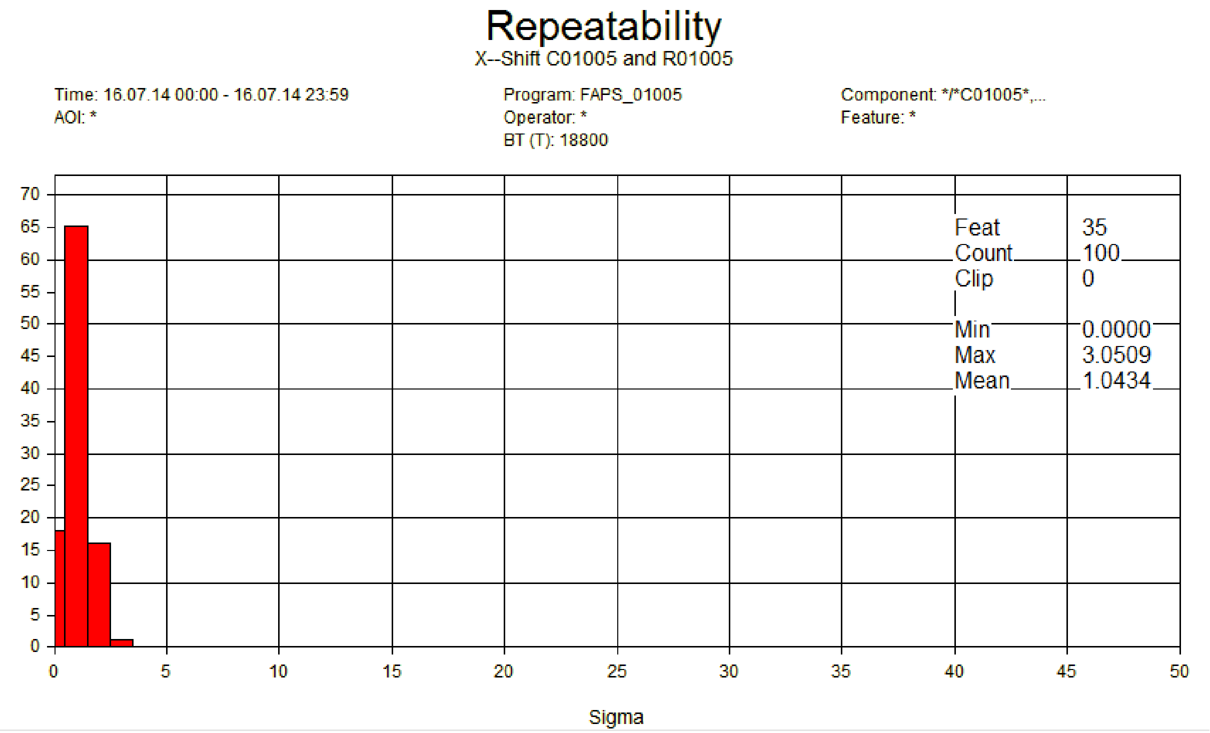


Image 9: Both the AOI system and the inspection program were examined for stability, measurement capability and reproducibility before the actual measurement.

4 Evaluation and discussion of the results

When the components were measured, a total of around 1500 components were classified as tombstones. Therefore, the influencing factors for tombstone formation and the self-centering effect were studied separately.

4.1 Evaluation of the occurrence of tombstone effects

An initial general consideration of the emergent defects first pointed out that detected tombstoning occurred twice as often on the capacitors as on the resistors, which with a height of about 120 µm are only about half as tall as the capacitors. This behavior is fairly evenly distributed among all pad geometries. Significant differences between the respective layouts were already apparent in their tombstone characteristics; here, particularly unusual forms such as circular pads (e.g., layouts A and G) or geometries with diminished dimensions (e.g., layout PY) had low tombstone rates (cf. Image 10). One special form that was considered (layout D) evinced the worst results in both its tendency toward tombstone formation and in the later evaluation of the self-centering effect, and so cannot be recommended from among the selected dimensions.

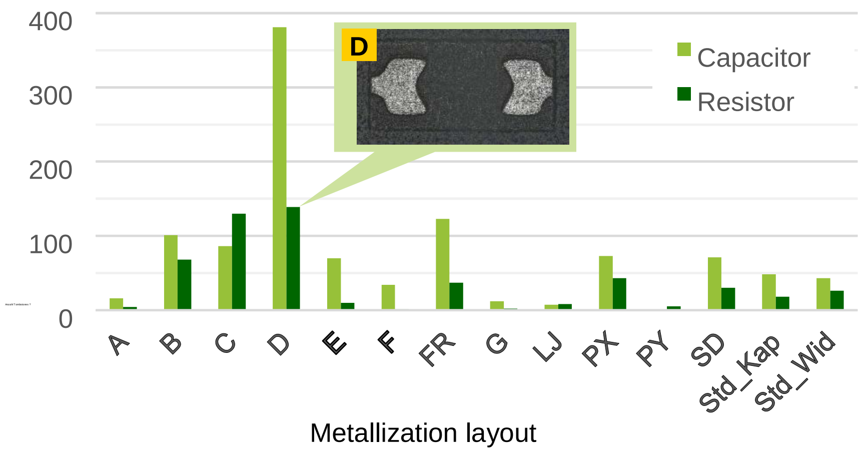


Image 10: Distribution of tombstones among the different pad geometries (separated into CC01005 and CR01005)

Significant differences were evident in a separate observation of the solder paste materials used; only around a quarter of all tombstone defects occurred with paste from manufacturer B (cf. Image 11). A definite trend was evident for paste material B; paste type 5 and use of a 100-µm-thick print stencil exhibited lower defect rates. In contrast, processing with paste type 4 from manufacturer B showed a decreased tendency to form tombstones.

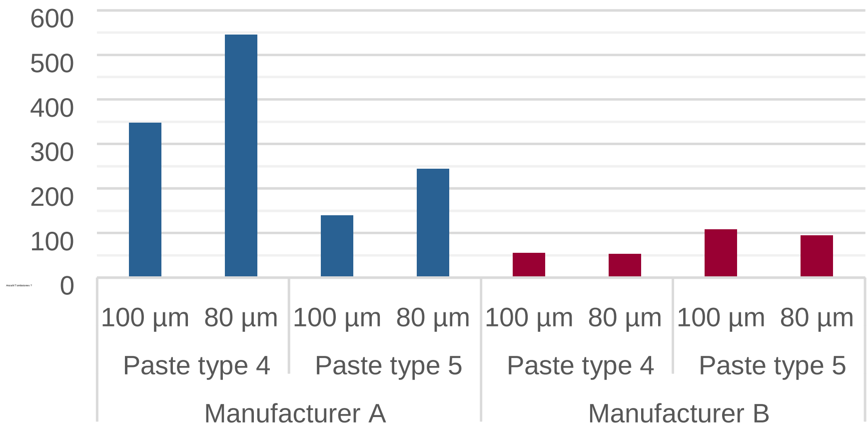


Image 11: Paste material A shows significant differences compared to paste material B.

A pre-arranged displacement of component positions supports the assumption of a higher tendency toward tombstone formation in the reflow process (cf. Image 3). When subdivided into their respective positions before the solder process, most tombstone defects occurred on the components with displaced rotation. A horizontal displacement in the x-direction also had a significant effect on tombstone formation. On components with no displacement or with vertical displacement in the y-direction, comparatively low defect patterns occurred; here, the y-direction especially stands out more positively, with less defects than the reference assembly with no displacement (cf. Image 12). A majority of the tombstones which occurred without programmed assembly displacement can be attributed to pad layout D.

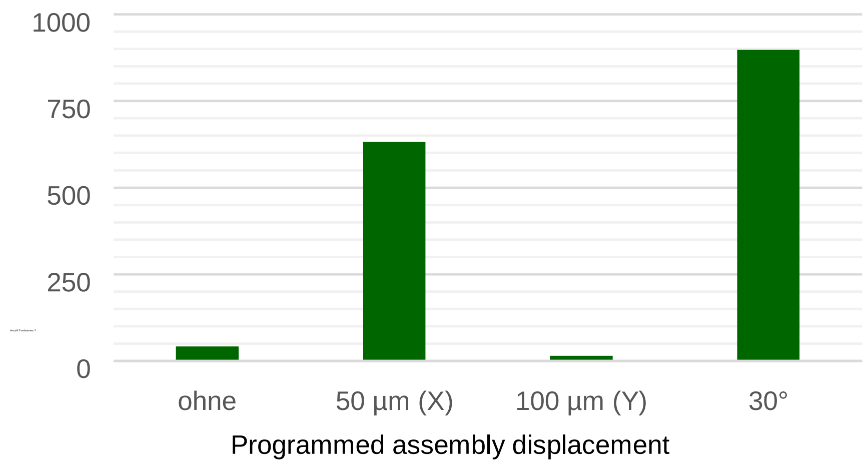


Image 12: Tombstones occur primarily when the component is horizontally displaced and rotated.

4.2 Self-centering behavior of 01005 components

First the reference electronic assemblies processed without pre-arranged assembly displacement were analyzed. An observation of all pad geometries yields a mean value of x = 3.97 µm (standard deviation σ = 7.02 µm) or y = -5.20 µm (σ = 10.51 µm) for the positioning after the reflow process. The rotation had a mean of 0.06° (σ = 2.19°). Here, the pad geometries of the metallization had the greatest effect on component position; the horizontal and vertical displacement from the target position differed for the various connection surfaces. This precludes identification of an optimal layout with no further effort, thus calling for exploration of the specific application case to find a suitable evaluation method. Additional effect calculations indicate that resistors have better positioning relative to the target position than do capacitors. The evaluation of solder paste manufacturer, on the other hand, is equivocal; when paste print results were successful, the use of paste type 4 showed no significant disadvantages against paste type 5. The effect of the stencil thickness selected is also insignificant in this part of the evaluation.

Evaluation of the measured positions of components floated into place establishes metallization as the most significant factor for all assembly variants having displacement and rotation. Hereby, on all electronic assemblies with programmed assembly displacement, resistors demonstrate a greater tendency toward self-alignment and therefore fewer deviations from the target position than capacitors; this effect is especially evident with vertical displacement in the y-direction. On the whole, including solder pastes from different manufacturers did not have any significant effect. As well, paste type 4 had no significant disadvantages compared to paste type 5. In individual cases, a stencil thickness of 100 µm resulted in improved component floating behavior as compared to an 80 µm stencil.

The different floating characteristics of the components first became evident in a targeted evaluation based on a reduced combination of parameters in which, for example, individual combinations of pad layout, paste manufacturer and print stencil used were specifically evaluated. Furthermore, the data measured by the paste inspection (Solder Paste Inspection - SPI) delivered valuable information for considering the influence the solder paste deposit had in the stencil printing process; in particular, transfer efficiency and thus, transferred paste volume, take the focus. The additional correlation of the data gained through SPI and the AOI measurement conducted during the test offers the greatest potential for a holistic evaluation embracing the entire process chain, to provide the basis for a better description of the causes behind defect patterns and floating behavior.

5 Summarizing evaluation and outlook

Within the context of these investigations, 44800 components of size 01005 were processed under a wide variation in the process parameters and measured with AOI. The optical appearance of 01005 components itself set rigorous demands on the automatic optical inspection. The AOI system employed demonstrated the necessary stability, measuring equipment capability, and reproducibility. This meant the processed electronic assemblies could be inspected for tombstone formation and other defects such as component presence, solder joint quality, etc., with full process reliability. A highly precise position determination was also conducted, and identified component location in terms of x-, y- and φ-position relative to target position.

During evaluation of the test series, a distinction was drawn between tombstone formation and description of the floating behavior. Essentially, compared to the resistors, the capacitors exhibited a greater tendency toward the tombstone effect. The majority of tombstones were caused by horizontal displacement and rotation during component assembly. Pad design, as well as solder paste manufacturer, have a significant influence on the process result. Even with the self-centering effect, the design of the pad geometry on the printed circuit board had the greatest impact on component floating behavior. Resistors have a greater intrinsic tendency to realign themselves during the reflow soldering process. The evaluation of the influence of a combination of solder paste manufacturer, paste type and stencil thickness used always requires a special analysis which must be adapted to the specific application. Since a multitude of effects and interrelations are significant in determining the process result, each production parameter must be considered individually if the influencing factors are to be evaluated with better accuracy. Based on previous evaluation of the results, an "optimum" pad layout for 01005 components is always a compromise made under consideration of all the influencing factors.

www.faps.de, www.viscom.de

6 Acknowledgements

Part of the results presented here originated within the context of the research project "01005 process windows". The IGF Initiative 17420 N of the Research Association on Welding and Allied Processes e.V. of DVS, Aachener Straße 172, 40223 Düsseldorf, was supported through the AiF under the aegis of the program to support Industrial Community Research and Development (IGF) with funds from the Federal Ministry of Economics and Energy on the basis of a decision by the German Parliament. Our special thanks to all members of the project steering committee, who supported this project as consultants with physical assets as well as invaluable information.

Bibliography

[1] Beer, D.; Funke, H.-J.: Applikationsbericht zur AOI von DFN-Bauteilen. In: PLUS – Produktion von Leiterplatten und Systemen (2014), No. 4, Pgs. 819-826

[2] DIN 32513-1, 01 Jan. 2005, Weichlotpasten - Teil 1: Zusammensetzung, Technische Lieferbedingungen

[3] Härter, S.; Läntzsch, C. ; Franke, J.: Gesicherte Verarbeitung von hochminiaturisierten Bauelementen der Baugröße 01005 in der Elektronikproduktion. In: DVS/ GMM (ed.): 7th DVS/GMM Conference, Elektronische Baugruppen und Leiterplatten (EBL), 2014, Pgs. 84-91

[4] Heilmann, N.: 01005 Assembly – From Board Design to the Reflow Process. In: OnBoard Technology (2008), Pgs. 54-59

[5] IPC 7351B-DE. 01 June 2010, Basisanforderungen an das SMT-Design und SMD-Anschlussflächen-Richtlinie

[6] IPC-J-STD 005, 01 Jan. 1995, Requirements for Soldering Pastes

[7] Krippner, P.: Prozessoptimierung mit 3D-SPI: Mehr als nur Fehlerdetektion. In: Elektronik Produktion & Prüftechnik (2011), Pgs. 1-3

[8] Rösch, M.; Franke, J.: Characteristics and potentials of nano-coated stencils for stencil printing optimization. In: Proceedings of the Surface Mount Technology Association International Conference (SMTAI). Orlando, FL, 2010, Pgs. 816-822