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The effect of solder paste volume on surface mount assembly self-alignment

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Abstract

In surface mount assembly, the consistency of solder paste volumes and the placement of the components play a vital role in the movement of the chip components when they go through the reflow soldering process. These movements may lead to common assembly defects such as overhanging, tilting, nonwetting, and tombstoning. Components to be assembled in surface mount assembly have self-alignment nature, which is driven by the total internal energy including gravitational energy, surface tension energy, etc. in the molten solder attributed to various factors. The factors include 1) solder paste composition, surface energy, gravity; 2) process variations such as solder paste volume, solder paste location, the inequality of solder paste volumes at the two terminals of the passive component, and components location and orientation; 3) design parameters such as pad dimension, pad-to-pad spacing, and pad surface finish.
In this research, energy-based three-dimensional model is created to predict solder joint profile (shape). Three types of passive chip component are chosen to be the modelling examples to investigate the component self-alignment performance during the reflow soldering process. By nature, the molten solder being a bulk fluid always tends to minimize its internal energy towards mechanical equilibrium and it causes the passive component to move to the state of minimal energy. This movement leads the component to self-align. Thus, by creating an energy minimization model, we can simulate the process of component self-alignment and predict the solder joint profile, final location, and orientation of the passive component.
Experimental studies are performed to develop a data-driven prediction model and are compared with the simulated component for validation. The passive components are placed with intended misplacements and their positions are measured before and after soldering. A wide range of surface mount assembly imperfections are considered and intentionally studied to achieve a powerful dataset and better convergence.

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Keywords: Self-alignment, numerical simulation, surface mount technology (SMT), reflow soldering

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1.Introduction

It's the trend in recent years that the surface mount technology (SMT) demands the need for miniaturization, cost-effectivity, higher density package and higher performance [1]. Consequently, automated placement machines are facing real challenges because the reduction of components sizes leads to a lower relative positioning accuracy at the same speed of placement [2]. Besides placement accuracy, in the surface mount assembly, the consistency in solder paste volumes is also a significant factor in the passive component (mostly resistors and capacitors) movements when they go through the reflow soldering process. These movements may lead to common assembly defects such as overhanging, tilting, nonwetting, and tombstoning. Fortunately, the passive components to be assembled in the surface mount assembly have a self-alignment nature. Therefore, utilization of component self-alignment becomes one of the most effective methods to increase the package rate at relative low cost with high precision [3]. Moreover, we can avoid in this way the electrostatic damage, magnetic noise, and the difficulty of manufacturing some specially designed copper pad, which occurs in some researchers' previous work [3–6].

Extensive research has been done by researchers to investigate the factors that can influence the passive component self-alignment performance, including 1) the solder paste composition, surface tension, gravity, contact angle; 2) process variations such as solder paste initial location, the inequality of solder paste volume at the two terminals of the passive component, passive component placement; 3) design parameters such as component weight, shape, size, metallization; pad size, shape, and surface finish [1–5]. Based on the simulation and experiment results, A.M. Najib concluded that the solder with larger surface tension and smaller contact angle can reduce the self-alignment error. Oliver Krammer, in 2013, found that the self-alignment performance in the component width-direction tends to be better than the performance in component length-direction, which can be explained by the restoring force in those two directions. He also concluded that the present of the sidewall metallization had a good influence on self-alignment performance [2]. Kaiji Sato, in 2002, executed some experiments to examine the effect of component shape on the self-alignment performance. His experimental results showed that the hexagonal boundary pattern component had better performance than components with a different boundary pattern[4].

In this study, a three-dimensional (3D) model was built to predict the solder joint profile and to investigate the effect of solder paste volume on the self-alignment performance of a passive component. The model was created by Surface Evolver to simulate the motion of the passive component during the solder reflowing process [7]. The 3D model is based on energy minimization of the liquid solder, which always tends to minimize its internal energy towards mechanical equilibrium; this causes the component to move to the state of minimal energy [8]. Based on this 3D model, the profile of solder joint and the location of the passive components with different initial misplacements are predicted. It is observed that the solder shape is obviously different when we use different amounts of solder paste, which will also change the solder wetting area on the copper pad. Moreover, when the solder volumes are different, the passive component will be slightly offset from the center towards the side of a smaller amount of solder. The self-alignment performance in the component width-direction tends to be better than the component length-direction. The analysis of restoring force and torque are presented to explain these phenomena. The simulation and experimental results showed good conformity and can be extended for different cases.

2.Theoretical background of the simulation

2.1 The introduction of Surface Evolver

Many numerical studies related to predicting the solder joint profile and calculating the restoring force and torque utilized the public domain software Surface Evolver. Surface Evolver is a finite element program that minimizes the energy of a surface defined by geometrical and physical constraints. The surface is represented as a simplicial complex that will be divided into many triangular facets. The displacement, force and energy on each vertex of those triangular facet will be calculated to determine the final shape with minimal energy. The total energy can include surface tension energy, gravitational energy and other forms of energy. The minimization is done by evolving the surface down the energy gradient. In Fig. 1, it is an example of evolving a liquid cube to a sphere

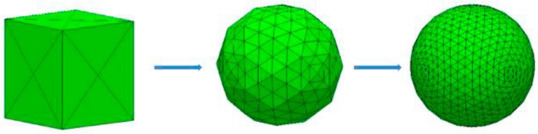


Fig. 1. The energy minimization of the liquid cube evolved by Surface Evolver

with minimized energy by Surface Evolver [9]. The final shape of the liquid will be a perfect sphere regardless of the effect of the gravity.

2.2 Energy minimization and force calculation

The displacement of the passive component is governed by the surface tension force linked to the minimization of the molten solder surface area along with the gravitational forces. The gravitational forces are exerted by the molten solder and component weight [9–11]. Therefore, we consider only the molten solder surface tension and the gravity of solder paste and passive components to calculate the total energy and the net restoring force and torque.

Thus, the total energy in the self-alignment system can be calculated by

$$E_t = E_s + E_g \tag{1}$$

The surface tension energy can be calculated by:

$$E_s = \int \gamma \ d_s$$

$$E_s = \gamma * S \tag{2}$$

Where γ is the surface tension of the molten solder, S is the free surface of the molten solder joint that will evolve to a most stable shape with the minimal total energy.

The gravitational potential energy can be calculated by

$$E_g = G * \rho * \iiint z \, dV \tag{3}$$

Combined with the divergence theorem, we can have:

$$E_g = G * \rho * \iint \left(\frac{z^2}{2} * \vec{k}\right) d\vec{S} \tag{4}$$

The integral above is taken over each facet that bounds the molten solder body.

Nomenclature

E	energy, dyne*cm
γ	surface tension, dyne/cm
S	area, cm^2
G	gravitational acceleration, cm/s^2
ρ	density, g/cm^3
V	volume, cm^3

Then, the total energy in the self-alignment system is the summation of the surface tension energy and the gravitational potential energy of the passive component.

As we have mentioned, the self-alignment performance is governed mainly by the molten solder surface tension force and the gravitational force of the passive component. To simplify the three-dimensional model, we consider only these two forces to calculate the restoring force and torque that are exerted on the passive component. The force schematic of the passive component is presented in Fig. 2. The x axis is along the component length direction.

The calculation of the restoring force is based on the principle of virtual work by finite differences [7]. We first evolve the system to a minimal energy state, then manually move the component to a certain direction with a significant small displacement 2*δq. Then the total energy of the system is changed, which would generate a restoring force in the opposite direction of the displacement. We can determine the restoring force by

$$F = -\frac{E(q+\delta q) - E(q-\delta q)}{2*\delta q} \quad (5)$$

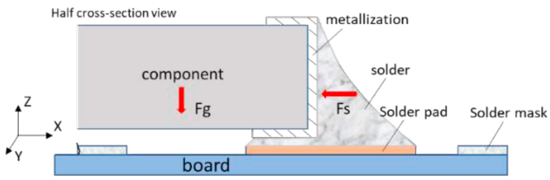


Fig. 2. Surface tension and gravitational force on the passive component

Obviously, the accuracy of the restoring force will depend highly on the magnitude of the virtual displacement δq due to the nonlinearity of the energy. Thus, δq should be chosen properly according to the desired precision.

In the same manner, the restoring torque can be calculated by manually rotating the passive component with a virtual angle 2*δθ. Because the rotation about x, y, z axis will not change the gravitational potential energy passive component, we can denote the total energy change by the change of the molten solder surface tension energy. Then, the restoring torque will be calculated by

$$T = -\frac{E(\theta+\delta\theta) - E(\theta-\delta\theta)}{2*\delta\theta} \quad (6)$$

Next, we can implement the restoring force and torque calculation concepts in our model. By calculating the restoring force and torque at different locations and different angles we can analyze the movement of the passive component and predict its final location and orientation.

3. Modeling of passive component self-alignment

3.1. Self-alignment modes

In the process of self-alignment, there are four movement modes defined as (1) shifting, in-plane translation in X-Y plane; (2) lifting, the vertical movement in Z direction; (3) twisting, rotation about Z axis; (4) tilt, rotation about X,Y axis [12]. However, the in-plane shifting and twisting about the z axis tend to be the main concern in the surface mount assembly (SMA) mass production line. In addition, because of the simplification of the model, in this study, we mainly focus on the component shifting and twisting motions. With respect to different self-alignment modes, the calculation of restoring force and torque have been presented.

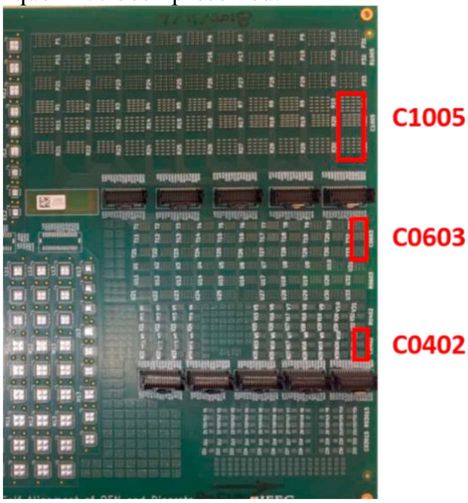


Fig. 3. The test PCB with three types of capacitor on the surface

3.2. Some basic assumptions of the model

- Only surface tension force and the component gravity will be taken into consideration; other forces, which are not dominant in the system such as the friction and the hydrostatic force of the molten solder will be neglected.
- Assume the wetting contrast between copper pad and solder mask surface is infinitely strong, which means the molten solder will be perfectly constrained by the copper pad edges without any overspreading. It is proven by the cross-sectional view that the solder mask can effectively prevent the molten solder from overspreading; see Fig. 4.
- The chemical reaction is not considered in this model.

3.3. Modeling materials and solder profile prediction

In this study, three types of chip capacitors (C1005, C0603, C0402) on the test printed circuit board (PCB), (Fig.3) were chosen as our passive components in the self-alignment model. On this PCB, SAC305 solder paste is used; the solder paste parameters are shown in Table 1. For the three types of capacitors, copper pads with different designed dimensions are used. The parameters of capacitors and copper pads are shown in Table 2.

Table 1. Model parameters of solder SAC305

Solder type	Surface tension (dyne/cm)	Density (g/cm^3)	Contact angle
SAC305	544.9 [1]	7.361	20^0

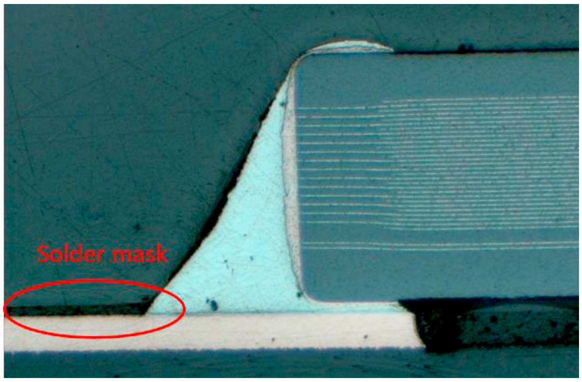


Fig. 4. C1005 cross-section view by optical microscope

Table 2. The parameters of passive components and solder paste pads

Passive component type	Size (cm) L× W× H	Weight (mg)	Metallization width (cm)	Designed solder paste volume (cm^3)	Pad dimension L× W (cm)	Vertical distance between pad and component (cm)
C1005	0.1×0.05×0.04	1.6	0.02	2.85×10^{-5}	0.05×0.056	0.0017 (measured)
C0603	0.06×0.03×0.023	0.33	0.015	7.77×10^{-6}	0.03×0.034	0.0012 (measured)
C0402	0.04×0.02×0.013	0.09	0.01	3.29×10^{-6}	0.02×0.022	0.0008 (measured)

Then, the three-dimensional self-alignment model is developed by utilizing the Surface Evolver software to predict the solder joint profile and the self-alignment performance of those capacitors. According to the above parameters, the initial solder joint profile is defined based on the wetting area, contact angle and component geometry (Fig. 5). In the initial solder profile, the molten solder is completely constrained by the copper pad edges and the solder contact angle on the copper pad is defined as 20^0.

After we input the solder initial profile, the Surface Evolver software will evolve the initial solder profile towards the energy minimization and stop at the mechanical equilibrium state to generate the final solder joint profile. By defining different solder paste volumes, we can obtain different solder joint profiles. In Fig. 6, the three types of solder joint profiles with different percentages of designed solder paste volume are generated by simulating capacitor C1005. It shows that the final shape of the molten solder will be affected by the solder paste volume and the copper pad size. If the copper pad size is big enough, the molten solder will be able to spread freely to reach its contact angle of 20^0, as shown in Fig. 6(a). Inversely, if the copper pad size is too small compared to the solder paste volume, it cannot provide enough space for the molten solder to spread freely. Then the molten solder will be constrained by the boundary solder mask eventually. As a result, the contact angle between the molten solder and the copper pad will be bigger than 20^0, as shown in Fig. 6(b) (c).

To enhance the predicted solder joint profile results, we use the automated optical inspection (AOI) machine to inspect the solder joint profiles of some capacitors on the production line and compared the profiles with the simulation results, in Fig. 9. It shows good conformity between predicted results and the real samples. In addition, some capacitors on the test PCB with different solder paste volumes were picked to be cross-sectioned (see Fig. 7). According to the sample cross-section images, the solder joint profiles generated are very close to the realistic samples by the model, which means the solder joint profile prediction model is conceivable.

Furthermore, the contact angles of molten solder on the copper pad in capacitors C0402, C0603, C1005 with respect to different solder paste volumes are generated by the simulation, in Fig. 11. As we can see, there are four stages (A, B, C, D) during the change of molten solder contact angle in capacitor C1005 and C0603. In stage A, the molten solder can spread freely on the copper pad so that the contact angle remains around 20^0. When the molten solder reaches the copper pad edge, it starts to be constrained, so the contact angle increases, which is stage B. When the molten solder is fully constrained by the copper pad edge, the contact angle stops increasing and the molten solder will clamp up along the capacitor vertical sidewall, which is stage C. When the molten solder reaches the top edge of the capacitor sidewall, it will be constrained by the top edge, and the molten solder contact angle will start increasing again, which is stage D. However, the designed solder paste volume in capacitor C0402 is too large compared to its copper pad size, (See Table 2), so that the molten solder is fully constrained by the pad edges when the solder paste volume is only 30% of the designed volume. Thus, the curve of the solder contact angle change in capacitor C0402 shows only stage D. In Fig. 10, it presents the foregoing stages when the molten solder spread in the copper pad.

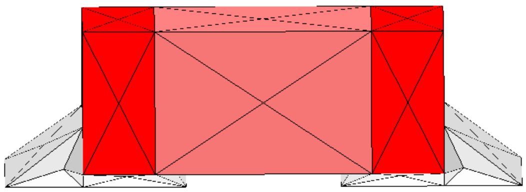
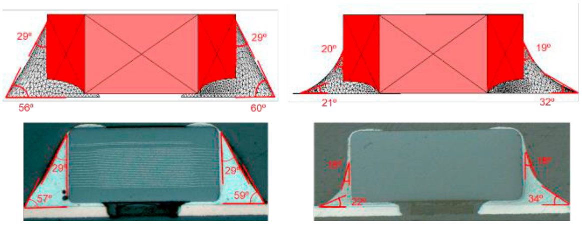


Fig. 5. User-defined solder joint initial profile before reflowing

(a) (b) (c)

Fig. 6. The Predicted solder profile with volume left/right: 50%/50% (a), 100%/100% (b), 150%/150% (c) Of designed volume



(a) Solder paste volume: Left 105%, right 107% (b) Solder paste volume: Left 55%, right 74%

Fig. 7. Solder joint profiles from simulation and sample cross-section, angles measured by software Axio Vision

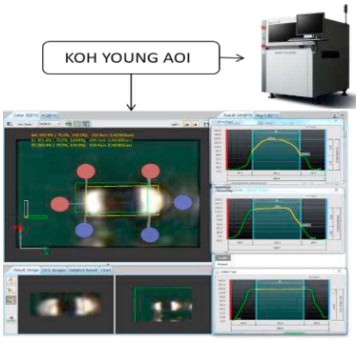


Fig. 8. Automated Optical Inspection

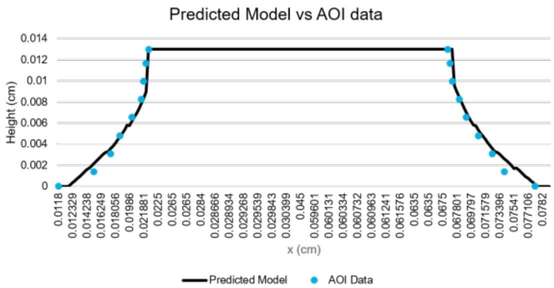
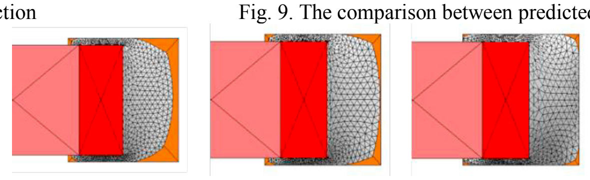
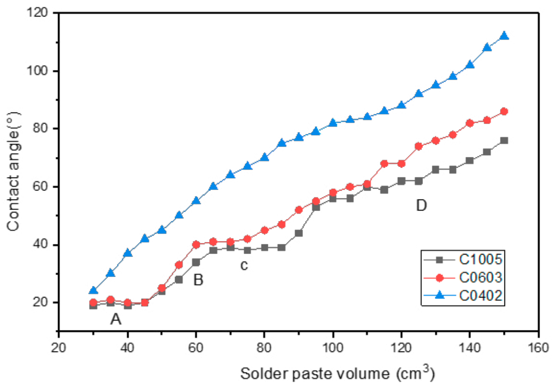


Fig. 9. The comparison between predicted and simulated solder joint profile



(a) (b) (c)

Fig. 10. The spread of molten solder on the copper pad, (a) spread freely, (b) molten solder reaches the copper pad edge, (c) molten solder fully constrained in copper pad



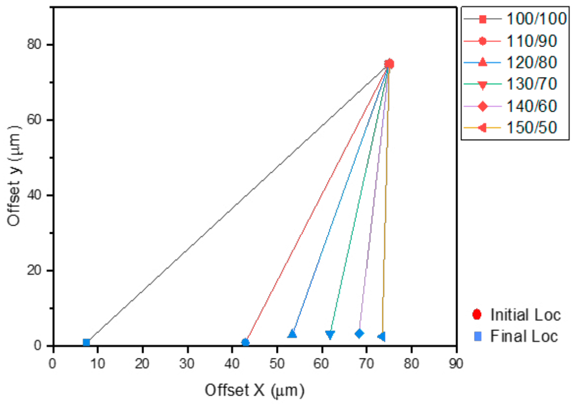


Fig. 11. The change of contact angle under different solder paste volumes

Fig. 12. Passive component self-alignment performance under inequal solder paste volumes

3.4. The effect of solder paste volume on passive component self-alignment

Due to the molten solder surface tension and energy minimization nature, if we have exactly the same amount of solder paste at the two terminals of the capacitor, the capacitor will theoretically self-align perfectly in the center. Because the same amount of molten solder at the two terminals of the capacitor will generate the same amount of restoring forces in opposite directions, the whole system tends to be symmetric, which leads to the perfect self-alignment. However, if the solder paste volumes are inequal, due to the accuracy of solder volume control system, the passive component will have relatively poor self-alignment performance even disconnection.

We simulate the self-alignment performance of capacitor C1005 with 100%/100%, 110%/90%, 120%/80%, 130%/70%, 140%/60%, 150%/50% of designed solder paste volume at left and right terminals of the capacitor respectively. As shown in Fig. 12, the self-alignment performance, which is demonstrated by the passive component final location, is much better when the solder paste volumes at the left and right terminals of the capacitor are equal. Naturally, when the solder paste volumes are inequal, the passive component will be pushed to the side with a lesser amount of solder paste during the reflow soldering process.

The effect of component initial misplacement on the self-alignment performance is also investigated though the simulation. The initial component misplacements in x and y direction range from 20~100 µm, 10~50 µm respectively. After the reflow soldering process, all these components move back to somewhere around the center, which means the initial misplacement of the component will theoretically not affect the self-alignment performance.

However, it is noticed that the components have better self-alignment performance in component-width direction (y) compared to component-length direction (x). In those nine cases, as shown in Fig. 13, the final offsets in x direction vary from 0.42 µm to 8.5 µm, while in y direction the offsets vary from -0.73 µm to 0.98 µm. It means when the passive component moves closer to the center, the restoring force in x direction is not big enough compared to the restoring force in y direction. In the next section we investigate the restoring profile and the twisting motion during the capacitor self-alignment.

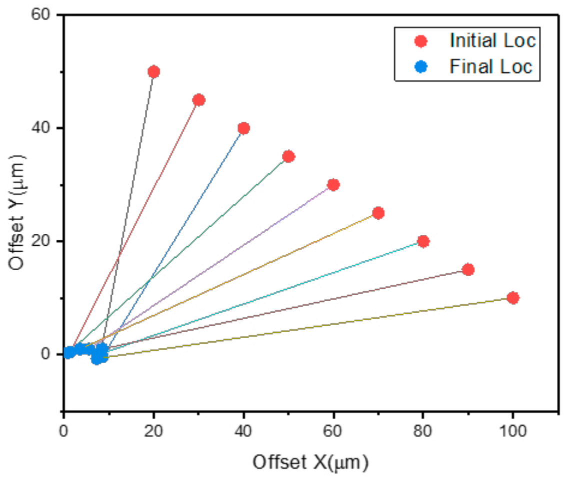


Fig. 13. The component self-alignment under different initial misplacements

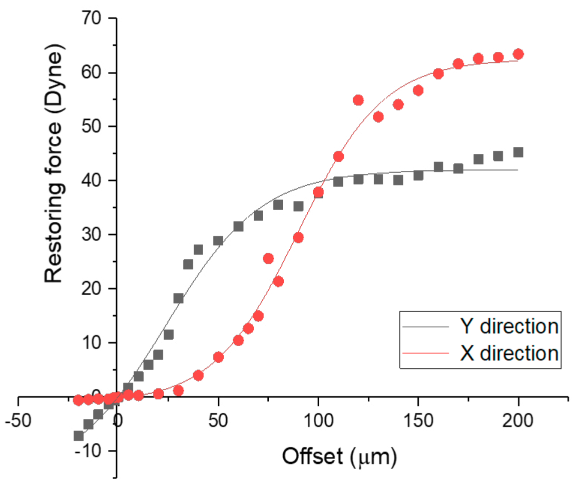


Fig. 14. The restoring force schematic of passive component with different solder volumes on the two sides

3.5. Restoring force and torque during passive component self-alignment.

Because the self-alignment performance is related to the restoring force and torque during the reflow soldering process, analysis of the restoring force and torque will help us better understand the passive component self-alignment.

The capacitor C1005 with 100%/100% of designed solder paste volume at the two terminals is used in the simulation.

Based on the principle of virtual work that we mentioned in section 2.2, the restoring forces in x and y direction during the passive component self-alignment are calculated and the force profiles are presented in Fig. 14. It is obvious that the restoring force profile in y direction is a convex curve, which means the passive component still has enough driving force provided by the molten solder when it is moving close to the center in y direction. However, the restoring force profile in x direction is a concave curve, and when the x offset is within 0 ~ 30 μm, the force is too small to move the passive component further. Thus, the component can stop at any place around 0 ~ 30 μm, which confirms the result that the self-alignment performance in y direction is better than in x direction.

The restoring forces in x and y direction can be further explained by the force diagram in Fig. 15. Fst1 and Fst2 are the restoring forces generated by the molten solder at the left and right sides, respectively. When the component has an offset in y direction, Fig. 15(a), the y component of the restoring force Fst1 and Fst2 will be in the same direction. Then the total magnitude of the restoring force in y direction is

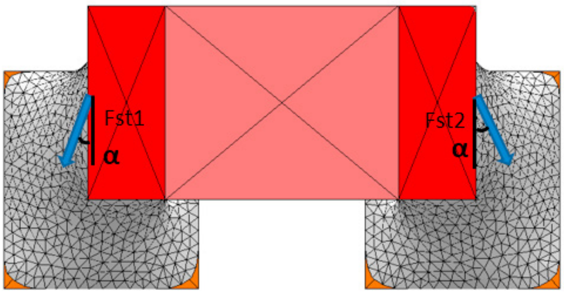
$$Fst = Fst1 * \cos(\theta) + Fst2 * \cos(\theta) \qquad (7)$$

While in x direction, the restoring forces generated by the molten solder on the left and right sides are in opposite directions, see Fig. 15(b), which means the net restoring force in x direction is

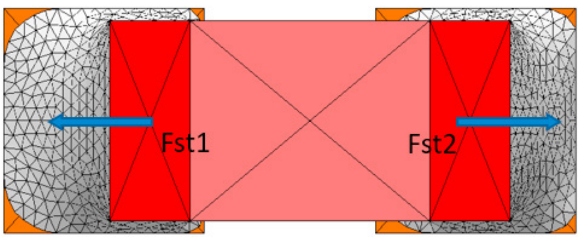
$$Fst = abs(\,Fst1 - Fst2\,) \qquad (8)$$

When the passive component is moving close to the center in x direction, the restoring force will decrease significantly, which explains the relatively poor self-alignment performance in x direction.

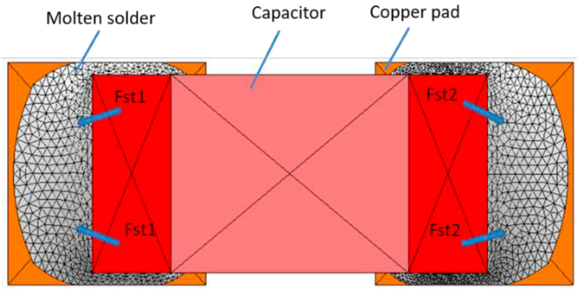
In industrial practice, the rotational misplacements are also a concern in surface mount technology (SMT). In this study, we have investigated the effect of the solder volume on passive component rotational self-alignment in z direction, which is called “twisting”, which we mentioned in section 3.1. In the simulation, the initial twisting angle α was set as 10^0 and -10^0. Due to the molten solder self-alignment nature, the passive component will rotate to 0^0 in z direction. During this process, the restoring torque is recorded, Fig. 17. According to the restoring torque profile, when the



(a)



(b)



(c)

Fig. 15. The passive component force diagrams under misplacement in x and y direction

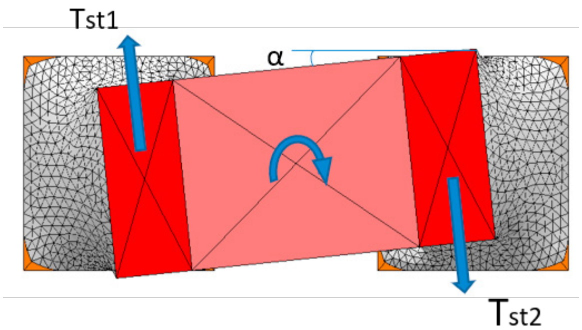


Fig. 16. The passive component with rotational misplacement α in z direction

total amount solder pastes on the left and right sides are the same (200%), there is no significant difference in the restoring torque. Because the total restoring torque is a summation of the torque generated by the molten solder on the left and right sides, (Fig. 16), if the total amount of the solder paste is the same, it will generate the same amount of restoring torque.

To confirm this result, we use balanced solder paste volumes, but the total amount is set as 100%, 150%, 200%, 250%, and 300%. The initial twisting angle α is still set as 10^0 and -10^0, Fig. 18. It shows that when the total amount of solder paste volume decreases from 300% to 100%, the total restoring torque will decrease successively. Therefore, it enhances our result that the twisting self-alignment will be affected mainly by the total amount of solder paste volume.

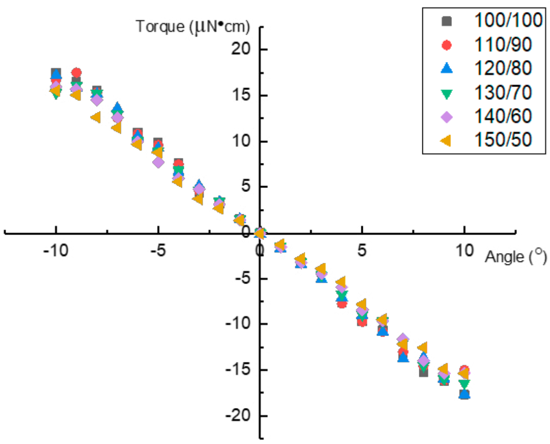


Fig. 17. The restoring torque under different unbalanced solder paste volumes

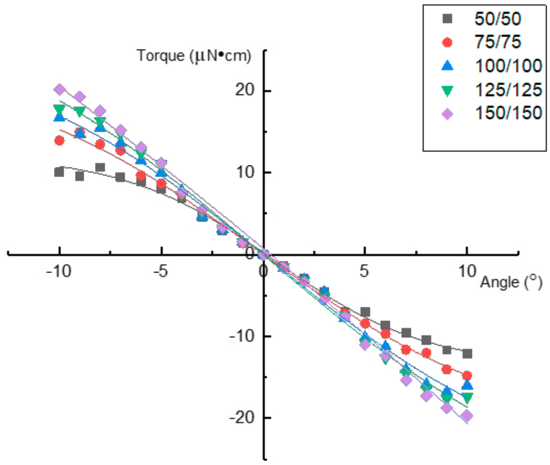


Fig. 18. The restoring torque under different balanced solder paste volumes

In addition, the effect of copper pad size on the restoring torque is investigated. In the model, we increase the width of the copper pad by 1.25 times. The restoring torque with equal solder paste volumes and relative bigger copper pad is presented in Fig. 19. As we can see, the restoring torques decrease after we increase the pad size, which means the twisting self-alignment is not as good as the previous case. Based on the result, we can conclude that the component twisting self-alignment performance can be improved by designing a proper copper pad size.

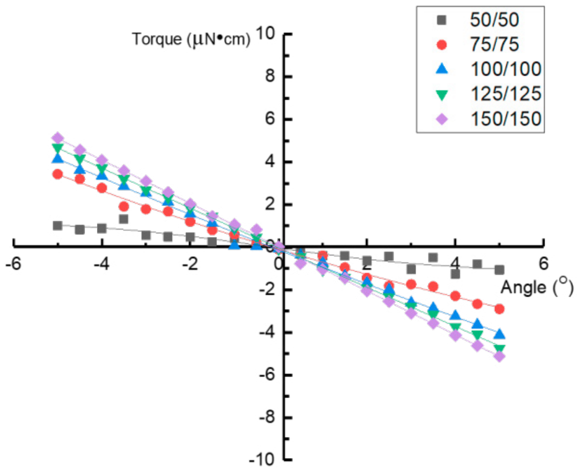


Fig. 19. The restoring torque after the copper pad width is increased by 1.25 times

5. Conclusions and discussion.

In this study, the effect of solder paste volume on the solder joint profile prediction and passive component self-alignment performance have been investigated. The profile of the component solder joint is decided by the solder paste volume, molten solder contact angle, and copper pad size. If the copper pad size is big enough for the molten solder to spread freely, the solder joint will be a concave shape. Otherwise, the solder joint shape will be a convex shape.

When the solder paste volumes at the left and right terminals of the passive component are equal, the passive component can self-align well in shifting (translation in x and y direction) and twisting (rotation about z direction) motions. However, the self-alignment in y direction (component-width direction) showed better performance than in x direction (component-length direction). The force diagram has been analyzed to explain this phenomenon. Passive component twisting self-alignment was not affected by the inequality of the solder pastes at the left and right terminals. Instead, the total volume of solder paste will affect the twisting self-alignment. The restoring torques under equal and inequal volumes of solder paste have been presented to explain this phenomenon. Moreover, we conclude that the component twisting self-alignment performance can be improved by designing a proper copper pad size according to the designed solder paste volume and component size.

In this model, there are still some details that we should consider and improve, such as the reaction between the molten solder and copper pad, frictions, molten solder overspreading, passive component tilting about x and y axis, etc., which will affect the solder joint shape and self-alignment prediction. Based on the solder joint shape prediction, we can also investigate the fatigue life with respect to different types of solder joint shape[13]. These topics can be our future study.

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