Modelling the Self-Alignment of Passive Chip Components
during Reflow Soldering

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Abstract

In my research a 3D model was created to investigate the restoring force arising and the self-alignment occurring during reflow soldering; and simulations were performed to examine the assumptions given by the model. Besides, experiments were carried out to verify both the assumptions and the simulation predictions. Passive components with the size of 0603 (1.5 x 0.75 mm) were placed with intended misplacements and their position was measured before and after soldering. Three cases were examined: how misplacements perpendicular to the longer sides of components affects the restoring force, how parallel misplacements affect the same, and how a sidewall metallization on the component influences that. Based on the results, it is shown that the degree of restoring force is higher in the case of misplacements perpendicular to the longer side of components (x-direction) than in the case of misplacements parallel to that (y-direction). However, in the case of y-direction misplacements, the restoring force increases when sidewall metallization on the components is present.

Keywords

Self-alignment of passive components, reflow soldering, surface tension, Surface Evolver
1. Introduction

Reflow soldering is generally used for fastening components mechanically and connecting them electrically to electronic circuit assemblies [1,2,3]. Concerning today trends, the passive discrete components (resistors and capacitors) are getting smaller and smaller, as it is demanded by the continuous development of surface mount technology. Consequently, automated placement machines are facing real challenges since the reduction of components sizes leads to a lower relative positioning accuracy at the same placing speed. Nevertheless, it is an empirical fact that the inaccuracy of placement can be reduced to a certain extent due to the self-alignment of the components. However, the self-alignment models for passive chip components suffer from serious weaknesses, e.g. they are 2 dimensional. 3D models are available only for complex circuit packages such as BGA or CSP packages [4].

At the beginning of surface mount technology, the examination of the self-aligning movement of the components during reflow soldering was limited to passive discrete components of larger sizes, e.g. components with size code 1206 (3 x 1.5 mm). That time, the applied models were two-dimensional and mainly focused on the tombstone effect (when one of the component’s terminations lifts from the pad). The first force model has been described by Wassink and Verguld [5]. It is a simple two dimensional force model, which aim was to predict the moments acting on the component during soldering in order to prevent the tombstone effect. The model assumes that there is no solder on the left face of the component and it considers the solder fillet as a straight line instead of a curve. In addition, the model, due to its simple manner, does not take the hydrostatic pressure of the liquid solder into consideration.

A more complex model has been described by John R. Ellis and Glenn Y. Masada [6], which takes the hydrostatic and capillary pressure of the molten solder into account, and considers the solder fillet as a curve. However, it was a two-dimensional model like the
Wassink-Verguld model. The model comprises further simplifications; it assumes that the component is brick-shaped (i.e. rectangle in 2D) and its mass centre is in the geometrical centre of the body. In addition, the model presumes that the corner of the component is always in contact with the soldering surface (pad), and the component rotates around that point. Although the model includes many specific details – the meniscus of the solder is not considered to be a straight line, the force due to hydrostatic pressure is taken into consideration, and the chip component is allowed to be displaced along its pad length to illustrate the effect of component misplacements –, it is still a two dimensional model, so three dimensional motion of the components cannot be described.

Newer models describe mainly the motion of high lead count integrated circuits packages, such as QFPs (Quad Flat Pack) and BGAs (Ball Grid Array) [7–9]. Movements of flip-chips were also investigated [10–13] where the diameter of the solder bumps is smaller (50–100 μm) compared to BGA packages (400–800 μm) [14,15]. According to these models, the same forces support the movement of the components during soldering, as in the case of the passive chip components: namely, the surface tension force of the molten solder and the force of the hydrostatic pressure [16,17].

Although the high lead count IC packages have a great interest today, the size decrease of passive discrete components (e.g. 01005 – 400 x 200 μm) induces increasing positional offset due to the inaccuracy of placement machines. Therefore, a detailed analysis of the self-aligning movement during soldering of small passive components based on a 3D model is absolutely necessary.
2. Theoretical background of profile calculation

As can be seen from the aforementioned models, predicting a component movement during soldering is based on the solder profile calculation. Thus, investigations were performed defining the shapes for various boundary conditions [18–20]. After the profile calculation, the forces acting on the component can be determined. Two main methods spread to determine the solder profile; one is based on the principle of pressure continuity, while the other one is based on minimizing the energy originating from the surface tension and the potential energy.

The principle of pressure continuity claims that in a static solder fillet, no pressure gradients exist horizontally and the pressure in the vertical direction changes proportionally to the distance from the liquid surface (i.e. proportionally to the height of liquid column) [6]. Consequently, since the fillet profile decreases in height as a function of the distance from the chip component, a continuously changing pressure difference must exist along the profile as illustrated in Fig. 1.

To find the pressure drop across the fillet, ΔP, Laplace’s equation is used to relate the pressure drop and the fillet surface geometry. In its most general form the equation is:

\[ \Delta P = \gamma \left( \frac{1}{r_1} + \frac{1}{r_2} \right), \]  

where \( r_1 \) and \( r_2 \) are the radii of curvature of the fillet measured normal to the surface of the component face metallization. For two-dimensional models, the solution is:

\[ \frac{d^2 y}{dx^2} = \frac{1}{\gamma} \rho g y - \Delta P_0 \left[ 1 + \left( \frac{dy}{dx} \right)^2 \right]^{3/2}, \]  

where \( \gamma \) is the surface tension coefficient, while \( \Delta P_0 \) is \( P_{\text{solder}} - P_{\text{atmosphere}} \).
Equation (2) is a second-order nonlinear differential equation which solution defines the fillet profile. Once the correct profile is known, the points at which the surface tension forces and pressure forces act can be computed. In this approach, two boundary conditions are needed (i.e. the solder wets until the end of the pad and the height of the solder fillet is equal to the height of the component) and $\Delta P_0$ is an unknown, but for a three dimensional force model this principle cannot be used to determine the fillet profile.

Calculating the solder profile by minimizing the energy rests on that the equilibrium shape of a liquid meniscus at a liquid-gas phase boundary of a system – in which solid, liquid, and gaseous phases coexist – is given by the balance of forces acting on the system. In the case of reflow soldering, the liquid phase is the molten solder, the solid phases are the soldering surfaces (component metallization and pad), while the gaseous phase is the atmosphere of the reflow oven. When the boundary condition is that the solder wets until the end of the metallization (the contact angle depends on the volume of the solder), the energy of the system which should be minimized is given by equation (3) [21]:

$$E = E_S + E_G,$$  \hspace{1cm} (3)

where $E_S$ is the energy originating from the surface tension [22]:

$$E_S = \int \gamma dS,$$ \hspace{1cm} (4)

and $E_G$ is the potential energy [23]:

$$E_G = \int \int \int \rho \cdot g \cdot z \cdot dx dy dz,$$ \hspace{1cm} (5)

where: $\gamma$ – surface tension coefficient, $\rho$ – solder density, $g$ – standard gravity, $A$ – surface of the fillet.
When the boundary condition is set in a way that the end of the pad is not wetted by the solder (which is very common for lead-free solders), then the contact angle is equal to the wetting angle. In this case the term of energy due to the surface tension can be determined with the following equations. At first, divide the surface of the solder into three parts; \( A_0, A_1 \) and \( A_2 \) for indicating the surface on the liquid-gas boundary and the surface of the liquid-solid boundaries respectively (Fig. 2).

Then the energy originating from the surface tension will form as:

\[
E_S = \int_{A_0} \gamma_{LG} \, dS + \int_{A_1} \gamma_{LS} \, dS + \int_{A_2} \gamma_{LS_i} \, dS,
\]

where: \( \gamma_{LG} \) is the surface tension coefficient between the liquid-gas boundary and \( \gamma_{LS_i} \) is the surface tension coefficient between the liquid-solid boundary.

Besides, the Young equation claims that in a static liquid the balance between the surface tensions is the following:

\[
\gamma_{LS} = \gamma_{SG} - \gamma_{LG} \cdot \cos \theta
\]

By substituting (7) into (6) and by omitting the zero value terms, the following equation can be obtained [24]:

\[
E_S = \int_{A_0} \gamma_{LG} \, dS + \int_{A_1} -\gamma_{LG} \cdot \cos \theta_1 \, dS + \int_{A_2} -\gamma_{LG} \cdot \cos \theta_2 \, dS.
\]

where: \( A_0 \) – boundary area of the solder and the gas, \( A_1 \) – boundary area of the solder and the pad, \( A_2 \) – boundary area of the solder and the component metallization, \( \theta_1 \) – wetting angle on the contact line of solder and the pad and \( \theta_2 \) – wetting angle on the contact line of solder and the component metallization.
3. Modelling of passive components’ self-alignment

3.1. 3D self-aligning force model of passive chip components

Based on my model, mainly five forces are acting on the chip components during reflow soldering (Fig. 3.). The force originating from surface tension \( F_{st} \) is acting on the boundary contact line of the three phases which are the solder, gas, and component metallization. The forces originating from hydrostatic \( F_h \) and from capillary \( F_c \) pressure are acting on the area of the component metallization; while the force originating from dynamic friction \( F_\nu \) depends on the mass of the liquid solder which should be actuated. The fifth force is the gravitational force \( F_g \).

In the case of component misplacements (which are due to the placement machine inaccuracy) the main force, which promotes the self-alignment, is originating from the surface tension of the liquid solder. The surface tension force acts on the appointment place of the three phases. In general case, the appointment place of a three-phase system is a space curve, which is called as the contact line in soldering technologies. Therefore, the net force originating from the surface tension can be obtained by integrating term of the surface tension along the contact line (9), which is determined by the previously calculated solder fillet:

\[
\bar{F}_s = \int \gamma_{lg} \, d\vec{l}. \tag{9}
\]

The forces, originating from hydrostatic- and capillary pressures of the molten solder, push the component out from the solder. These forces are acting on the vertical face- and bottom side metallization of the component as illustrated in Fig. 4. \( F_h \) and \( F_c \). As mentioned before, the capillary pressure is the pressure difference between the two sides of a curved
liquid surface and that pressure drop across the fillet ($\Delta P$), can be determined by the Laplace’s equation (1).

Therefore, the force originating from hydrostatic- and capillary pressures ($F_p$) can be determined by integrating the pressure along the surface of the component metallization (10):

$$F_p = \int_{A_{cs}} \rho_s g \cdot h(\vec{r}) \, d\vec{S} + \int_{A_{cs}} \left\{ \gamma_{LG} \left( \frac{1}{r_1(b(\vec{r}))} + \frac{1}{r_2(h(\vec{r}))} \right) \right\} \, d\vec{S},$$  \hspace{1cm} (10)

where: $A_{cs}$ – surface of the component metallization, $\rho_s$ – density of the molten solder, $\vec{r}$ is the spatial vector, $h(\vec{r})$ – height of the liquid column, which is infinitesimally close to the point designated by the $\vec{r}$ vector on the $A_{cs}$ surface, $b(\vec{r})$ – point on the top of the liquid column, where the capillary pressure should be calculated.

The dynamic friction between the liquid and the solid phases slows the movement of the liquid phase. The force, originating from the dynamic friction between a solid and a liquid phase can be described by Newton Viscous Force equation [25], which reduces the self-alignment of the component in my case. The liquid (molten solder) can be considered as a series of horizontal layers. The top layer in the molten solder is infinitesimally close to the bottom side metallization of the component, and its speed is equal to the speed of the component movement. The speed of bottom layer is 0, equal to the speed of the pad. Thus, the decelerating force due to the dynamic friction is (11):

$$F_v = \int_{A_{cs}} \eta_s \cdot \frac{(\vec{v} - \vec{v}_0)}{d(\vec{r})} \, d\vec{S},$$ \hspace{1cm} (11)

where: $A_{cs}$ – surface of the component metallization, $\eta_s$ – viscosity of the molten solder, $\vec{v}$ – speed vector of the component movement, $\vec{v}_0$ – speed of the point at $d$ distance, which is 0 if it is on the pad (Fig. 5. – point $P_2$), and not 0 if the point is on the surface of the molten solder.
(Fig. 5. – point \( P_1 \)), \( d(\vec{r}) \) – distance between the pad or the surface of the solder and the point under investigation, which is designated by vector \( \vec{r} \) on surface \( A_{cs} \).

Consequently, the net force (12) acting on the component during reflow soldering is the sum of the above described forces and the gravity force:

\[
\vec{F}_{\text{sum}} = \vec{F}_{st} + \vec{F}_p - \vec{F}_v + \vec{F}_{\text{grav}}
\]

\[
\vec{F}_{\text{sum}} = \int_{v} \gamma_{LG} \, d\vec{l} + \int_{A_{cs}} \rho_s \cdot g \cdot h(\vec{r}) \, d\vec{S} + \int_{A_{cs}} \gamma_{LG} \left( \frac{1}{r_1(b(\vec{r}))} + \frac{1}{r_2(b(\vec{r}))} \right) \, d\vec{S} - \int_{A_{cs}} \frac{\eta \cdot (\vec{v} - \vec{v}_0)}{d(\vec{r})} \, d\vec{S} + \int_{V_{\text{comp}}} \rho_{\text{comp}} \vec{g} \cdot dV \tag{12}
\]
3.2. Predictions based on the 3D model

Positional offset of chip components should be investigated in two major directions; the 
\textit{x-direction} misplacement is the positional offset parallel to the shorter side of the component, 
while the \textit{y-direction} misplacement is the offset parallel to the longer side of the component. 
In the case of \textit{x-direction} misplacement, the forces originating from the surface tension aid the 
self-alignment at both solder joints symmetrically, as it is illustrated in Fig. 6.

In the case of \textit{y-direction} misplacement, the system is not symmetrical to its shorter side, the 
shapes of molten solders are different on the two faces of the component and the force 
originating from the hydrostatic pressure is greater on the face where the fillet of the joint is 
concave, as it is illustrated in Fig. 7. \((F_{p1}<F_{p2})\). The solder on the right face of the component 
pushes the resistor out from itself and aids the \textit{y-direction} self-alignment. The surface tension 
forces are different on the two faces, like the force deriving from hydrostatic and capillary 
pressure. Unfortunately, these forces on the two faces are opposite to each other therefore 
only their difference aligns the resistor. This predicts that the degree of resistor self-alignment 
is lower in \textit{y-direction} than in \textit{x-direction}.

Yet, it has been discussed in Section 2 that if the end of the metallization is not reached 
by the liquid solder, the contact angle will be equal to the wetting angle; but in the case when 
the end of the metallization is reached by the liquid solder, the contact angle depends on the 
volume of the solder. Furthermore, even if the volume of the solders \((V_1=V_2)\) is equal, the 
contact angle depends on the relative positions of the bodies (metallization) to be wetted, as it 
is illustrated in Fig. 8. \((\theta_1<\theta_2)\).
Therefore, it can be predicted that if metallization is present on the sidewalls of the component (like on chip capacitors), the surface tension forces on the contact lines of sidewall metallization will point to the same direction in the case of $y$-direction misplacement (Fig. 9.). The forces from hydrostatic pressure will form, as it is illustrated previously in Fig. 7. Normally, after a certain self-alignment, when the system is nearly symmetrical, forces $F_{st1}$ and $F_{st2}$ will be opposite to each other again.
4. Experimental

In this research, simulation and experimental measurements were carried out regarding the self-alignment of passive chip components. Self-alignment of two component types were compared; one type was a 0603 (1.5 mm x 0.75 mm) chip resistor which does not have sidewall metallization, while the other one was a 0603 chip capacitor which has sidewall metallization. A testboard (Fig. 10.) was designed and fiducial points were placed around all components for later positional measurements. The substrate of the testboard is FR4 glass-epoxy and the surface finish of the solder pads was immersion silver. For soldering the components, a tin-silver copper (SAC305) solder paste with particle size of 25–38 µm was used and deposited with a 150 µm thick, lasercut stainless steel stencil. For the soldering, an Essemtec RO06 reflow oven was used setting the peak temperature to 240 °C and the Time Above Liquidus (TAL) to 80 s according to industrial standards. The simulation and the experiments were performed side-by-side, thus the design parameters (pad dimensions, stencil thickness) of the experiments were included in the simulations.

As aforementioned, the simulation of self-alignment should be started with solder profile calculation. For this purpose, the widely applied Surface Evolver [26] software was used. The input parameters of the model are collected in Table 1.

The number of iterations and mesh refinements was verified with grid dependency test (Fig. 11.). The number of sum iterations (200) and refinements (4) used for the modelling is indicated with the black vertical line in the figure. After the grid dependency test, the accuracy of the solder profile calculation was verified with analysing a real solder joint cross-section and with comparing it to the calculated profile (Fig. 12.).
The accuracy of the profile calculation along the meniscus was mostly around 5 µm. In one case, the difference was a little bit higher, 15 µm, which can be possibly caused by voids having reached the surface of the solder fillet and having made that a little bit rougher. After the profile calculations, the restoring force was calculated for both component types in the misplacement range of 0–400 µm. The results are illustrated in Section 5.

Beside the calculations, experiments were performed with 0603 size chip resistors concerning the degree of self-alignment in case of $x$ and $y$-direction misplacement. After the solder paste deposition, resistors were placed with TWS Quadra semi-automatic pick&place machine with intended positional offset in the range of 0–600 µm in $x$-direction and in the range of 0–350 µm in $y$-direction.

The distance during the self-alignment of the components was determined with measuring the position of the components before and after soldering based on the guidelines of the IPC-9850 standard [28]. It advises placing fiducial points around the solder pads, as it is illustrated in Fig. 13. In order to determine the position of the SM component, the distance between the fiducial points and the corners of the component body should be measured and the offsets can be calculated with equations (13) and (14) respectively. The images of the misplaced and reflowed components were captured with an Olympus SZX9 microscope, and the positions were measured with image processing software (Fig. 14.). The resolution of the acquired images was 2.4 µm/pixel.
\[ x_{\text{offset}} = \frac{dx_1 - dx_2}{2} \]  
\[ y_{\text{offset}} = \frac{dy_1 - dy_2}{2} \]

For investigating the effect of sidewall metallization on the restoring force, two types of components: resistors (no sidewall metallization) and capacitors (sidewall metallization is present) were placed with intended \textit{y-direction} misplacements of \( \sim 200 \, \mu\text{m} \) and \( \sim 400 \, \mu\text{m} \). The distance travelled during soldering was calculated as mentioned before, but the results should have been weighted with the mass of the components because resistors have a measured mass of 2 mg, while the average mass of capacitors is 4 mg. Since the acceleration of a body is inversely proportional to its mass and the displacement of a body is directionally proportional to the acceleration, the value of the displacement is multiplied with mass of the components to make the cases of theirs comparable. In this way, the dimension of the distance travelled during soldering is \([\mu\text{m} \cdot \text{mg}]\).

5. Results

The results of the calculated restoring force are illustrated in Fig. 15. and Fig. 16. It can be said that the restoring force in the case of \textit{x-direction} misplacement is about two to three times higher than the \textit{y-direction} restoring force, which is in accordance with the prediction of my model discussed in section 3.2. The restoring force for the highest degree of misplacement is 450 \( \mu \text{N} \) and 150 \( \mu \text{N} \) for the \textit{x} and \textit{y-direction} offsets respectively.

Concerning the \textit{y-direction} restoring forces for both cases (there is a sidewall metallization on the component and there is not), the calculation results confirmed the
predictions. The restoring force is slightly higher when sidewall metallization is present on
the components (Fig. 16.). It can be observed as well, that even when there is sidewall
metallization on the components, the restoring force is still lower (max. 200 µN) compared to
the \textit{x-direction} restoring force (max 450 µN).

The calculation results were verified with experimental procedures too. Chip resistors
were placed with intended misplacements up to 600 µm in \textit{x-direction} and up to 350 µm in \textit{y-
direction}. The position of the components was measured with an optical microscope before
and after soldering, and the difference in position was calculated. The results of distances
travelled during soldering are illustrated in Fig. 17. They confirm the prediction of the model
and the results of the calculations (Fig. 15.) since the movement of the components was larger
in the case of \textit{x-direction} misplacements than in the case of \textit{y-direction} misplacements.

After investigating the self-alignment for misplacements in different directions, the self-
alignment of capacitors and resistors (i.e. components with and without sidewall
metallisation) was compared. They were misplaced in \textit{y-direction} with 200 and 400 µm, and
the distance travelled during soldering was measured like before. The measured distances
multiplied then with the mass of the components because capacitors weigh two times more
than resistors. The results are illustrated in Fig. 18., which confirms the results of the
simulation; the components with sidewall metallization can cover higher distance during
soldering due to the force of surface tension.
6. Conclusion

In my paper the self-alignment of surface mounted passive discrete components was investigated. The degree of restoring force was predicted by a 3D model and calculated with Surface Evolver. Besides, experiments were performed to make deduction for restoring forces which arise during reflow soldering. Based on the results, it can be said that the degree of restoring force is higher in the case of misplacements perpendicular to the longer side of components ($x$-direction – 450 $\mu$N) than in the case of misplacements parallel to that ($y$-direction – 150 $\mu$N). However, in the case of $y$-direction misplacements, the restoring force increases when sidewall metallization on the components (i.e. capacitors) is present (200 $\mu$N). These results would raise the necessity of revising the IPC-610 [29] standard which prescribes fairly loose rules regarding the misplacement of components parallel to their longer sides, and does not make a distinction between resistors and capacitors.
References


[26] http://www.susqu.edu/brakke/evolver/evolver.html, 2013.05.31


[29] IPC-A-610E – “Acceptability of Electronic Assemblies”, Developed by the IPC-A-610 development team including Task Group (7-31b), Task Group Asia (7-31bCN) and Task Group Nordic (7-31bND) of the Product Assurance Committees (7-30 and 7-30CN) of IPC, April 2010.
Figure Captions

Fig. 1. Principle of pressure continuity [6].

Fig. 2. Boundary condition that a solder does not reach the end of the metallization.

Fig. 3. The forces acting on the chip component during reflow soldering.

Fig. 4. Forces due to hydrostatic- and capillary pressures

Fig. 5. Calculating the force originating from the dynamic friction

Fig. 6. Restoring force in the case of x-direction misplacement

Fig. 7. Restoring force in the case of y-direction misplacement

Fig. 8. The wetting angle in the case of different relative positions of metallization

Fig. 9. Restoring force when sidewall metallization is present on the component

Fig. 10. Testboard for investigating the self-alignment of passive components

Fig. 11. Grid dependency test of the profile calculations

Fig. 12. The simulated solder profile on a cross-section sample

Fig. 13. Determining the positional offset of a chip component

Fig. 14. Measuring the position of a misplaced resistor

Fig. 15. Restoring force for x and y-direction misplacements

Fig. 16. y-direction restoring force on components with and without sidewall metallization

Fig. 17. Distance travelled by resistors for x and y-direction misplacements

Fig. 18. Distance travelled by resistors and capacitors in the case of y-direction misplacements
Table 1. Model parameters for solder profile calculation

<table>
<thead>
<tr>
<th>Component dimension [mm]</th>
<th>Pad dimension [mm]</th>
<th>Length of component metallization [µm]</th>
<th>Vertical distance between component and pad [µm]</th>
<th>Positional offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 x 0.8 x 0.43</td>
<td>0.76 x 0.96 (design)</td>
<td>250</td>
<td>25 (measured)</td>
<td>variable</td>
</tr>
<tr>
<td>Surface tension</td>
<td>Density of solder</td>
<td>Wetting angle</td>
<td>Solder volume</td>
<td></td>
</tr>
<tr>
<td>550 mN/m [27]</td>
<td>7360 kg/m³ [27]</td>
<td>18° (measured)</td>
<td>0.054 mm³</td>
<td></td>
</tr>
</tbody>
</table>
Atmospheric Pressure = $P_{atm}$

Pressure 1 = $P_{atm} + \Delta P_1 + \rho gh_1$

Pressure 2 = $P_{atm} + \Delta P_2 + \rho gh_2$

$\Delta P_1$ across fillet surface

$\Delta P_2$ across fillet surface

Equal pressure along horizontal lines
Figure 04
Figure 05
Figure 06

- **LEFT**
  - Double-headed arrow labeled \( A \)

- **TOP A-A**
  - "pad and solder"
  - "metallization"
  - "component"
  - "molten solder"

- **Diagram**: Two red arrows labeled \( F_{st1} \) and \( F_{st2} \) indicate forces acting on the component.

Click here to download high resolution image
solder pad component

fiducial point

\[ dx \]
\[ dy \]

\[ dx_1 \]
\[ dy_1 \]

\[ dx_2 \]
\[ dy_2 \]
Figure 14

The image shows a close-up view of a microchip with labeled measurements:

- \( dy = 514 \) px
- \( dx = 204 \) px

The scale at the bottom right indicates 1 mm.
Figure 17

The figure shows a graph plotting distance travelled versus positional offset. The graph includes two types of markers:

- ■: x direction misplacement
- ◇: y direction misplacement

The x-axis represents positional offset in micrometers (µm), while the y-axis represents distance travelled in micrometers (µm). The markers indicate the relationship between the positional offset and distance travelled for both x and y directions.