Determination of Friction Coefficient of a Press-Fit Pin in Thin Plating

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To determine the friction coefficient of a press-fit pin in thin plating, both experiments and three-dimensional finite element analysis are carried out. The compliant press-fit pins are assembled into printed circuit boards with two types of plated through holes, one is Cu and Sn plated and the other only Cu plated, and the load-displacement relationships of the pin during assembly are recorded. Based on the load-displacement relationships of the pin obtained experimentally and the nodal reactions of the pin contacting with the plated hole, obtained from numerical analysis, performed assuming a fiction-less condition, the friction coefficients of the pin in plated holes during assembly are successfully determined. The friction coefficient of the pin in the Sn/Cu plated hole exhibits a higher value than that for the Cu plated hole during assembly, due to the adhesion in the contacting region. In an attempt to check the validity of the determined coefficients of friction, different press-fit assemblies are considered, and the load-displacement relationships of the pin are predicted. The simulations are found to be in good agreement with experimental measurements. The retention forces between the pin and the plated holes are also predicted.

Key Words: Finite Element Method, Friction, Reliability, Press-Fit Assembly, Solderless Technology, Compliant Pin, Plated Through Hole

1. Introduction

Environmental considerations in the electronics industry have stimulated a worldwide movement to reduce the lead in the electronic products and to reuse or recycle the products(1). Lead-free soldering is a typical new technology for overcoming the environmental problem, but the soldering technology is basically inseparable from the problem of thermal mismatch of the components, which degrades the reliability of the electronic products. Also, the electronic parts assembled by soldering are difficult to reuse. Anisotropic conductive film (ACF) has recently attracted a growing interest as a post soldering technology due to its economic and environmental merits in the electronics industry(2)–(4), but the ACF technology is inferior to soldering from the point of mechanical and electrical requirements. Press-fit interconnection is an older type of electrical interconnection between the electronic components and the printed circuit board (PCB), invented in the early of 1970’s(5)–(7), and the solderless technology, which is free from thermal problems and permits the reuse of the electronic parts, has attracted considerable attention once more, due to the recent environmental and economic requirements(8).

An example of a compliant press-fit interconnection is shown in Fig. 1. The technique assembles the electronic parts utilizing a press-fit pin inserted into a plated through hole on the PCB, and the electronic parts are then connected to the PCB by utilizing the deformation of the pin as a spring [Fig. 1 (a)]. The retention force between the pin and the through hole is governed by the friction coefficient of the pin in the plated hole and the normal force applied to the contacting region. In order to realize reliable assembly, the retention force has to achieve the required
value, which depends on the purpose of the application and the environment in which the press-fit components will be used. A higher normal force on the contacting region produces a higher retention force, but it also results in higher stress in the PCB, leading to possible PCB damage [Fig. 1(b)]. Therefore, the assembly conditions, e.g. the shape of the pin, plating treatments, diameter of the through hole, etc., have to be optimized to reduce damage to the PCB, whilst maintaining sufficient retention force. However, the friction coefficient of the pin in plated hole is usually unknown, and it is thus difficult to predict the retention force from numerical analysis. Moreover, the friction coefficient of the press-fit pin in thin plating is affected by a number of factors, such as the surface conditions of the pin and the plating, the microstructure of the plating, sliding velocity, force, etc. Therefore, the measurements of the friction coefficients of the pin on the plated holes of the actual press-fit components are urgently required.

This paper proposes a methodology for determining the friction coefficient of the press-fit pin in thin plating during assembly. The compliant press-fit pins are assembled into the PCBs with two types of plated through holes, one is Sn/Cu plated and the other merely Cu plated. Three-dimensional finite element (FE) analysis of the press-fit assembly is carried out, assuming a friction-less condition. By using the load-displacement relationships of the pin obtained experimentally, together with the numerical results, the friction coefficients of the pin on the plated holes are successfully determined. Furthermore, by using the determined friction coefficients and the nodal reactions of the pin contacting with the plating surface obtained numerically, both the unknown load-displacement relationships for assembling the pins into the plated through holes and their retention forces are predictable.

2. Experiments

A compliant press-fit pin treated in this study is shown in Fig. 2. The press-fit pin was made of phosphor bronze, and the surface of the pin was coated with 3 \( \mu \)m thick Sn plate. The central width of the spring part of the press-fit pin before assembly was 1.19 mm, and the thickness of the spring part of the pin was 0.6 mm. Two types of FR-4 grade multi-layered PCBs, 1.6 mm thick, with different plated through holes, were prepared as shown in Fig. 3. The inner surfaces of the through holes on one PCB were Cu plated to a 25 \( \mu \)m thickness, followed by Sn plating to 3 \( \mu \)m thickness [Fig. 3(a)]. This was termed the ‘Sn/Cu plated hole’. The through holes on the other PCB

![Fig. 2](image)

Fig. 2 Details of the compliant press-fit pin used in this study: (a) Front view, (b) Side view

![Fig. 3](image)

Fig. 3 Schematic of the through holes: (a) Sn/Cu plated hole, (b) Cu plated hole
were plated only with 25 \( \mu \)m thick Cu [Fig. 3 (b)], and this was termed the ‘Cu plated hole’. 58 through holes were prepared in each PCB, at a pitch of 2.5 mm. The diameter of the holes, after plating, was 0.94 ± 0.03 mm. 27 press-fit pins were inserted, one by one, with a universal testing machine, and the load-displacement relationships of the pin during assembly were recorded at a cross-head speed of 833 \( \times 10^{-6} \) m/s. In order to measure the retention forces between the pins and the plated holes, push-out testing was carried out on all assembled pins in each PCB, where the testing machine and the cross-head speed were the same as in the press-fit assembly.

3. Numerical Analysis

3.1 FE model

To determine the nodal reactions of the press-fit pin in contact with the plated surface, three-dimensional FE analysis of the press-fit assembly was performed using Marc\(^{10}\). Figure 4 shows the 1/4 FE model used in this study. A rectangular coordinate system (\( x, y, z \)) was introduced, with an origin located at the center of the through hole on the surface of the PCB. The numerical analysis was performed without taking into account the friction between the pin and the plating, i.e. the friction coefficient was assumed to be zero. Here, the FE analysis was performed only for the Cu plated through hole because the Sn plating was very thin and such thin plating would never affect the nodal reactions of the pin contacting with the plating in the zero friction case.

3.2 Material properties

The material properties of the press-fit pin and the Cu plating obtained from experiments, found to the linear-hardening elastic-plastic materials, are summarized in Table 1. The stress-strain relationship is given by \( \varepsilon = \sigma / E \) for \( \sigma \leq \sigma_Y \), and \( \varepsilon = \sigma_Y / E + (\sigma - \sigma_Y) / E' \) for \( \sigma > \sigma_Y \), where \( \varepsilon \)

| Material       | \( \sigma_Y \) (MPa) | \( E \) (GPa) | \( E' \) (GPa) | \( \nu \) |
|----------------|---------------------|--------------|--------------|--------|
| Press-fit pin  | 710                 | 80           | 1.09         | 0.3    |
| Cu plating     | 305                 | 21           | 0.20         | 0.3    |

4. Results

4.1 Experimental results

The load-displacement relationships for the pin in the Sn/Cu and the Cu plated holes are shown in Fig. 6. Here, the displacement started to increase when the press-fit pin first made contact with the through hole. In both cases, the loads initially increased with increasing displacement, and, at a displacement of about 0.6 mm, the loads reached their maximum values. After that, the loads decreased with increasing displacement. The loads at the end of the load-displacement relationships for the Sn/Cu and the Cu plated holes were 63.3 and 48.0 N, respectively. The maximum loads observed during the load-displacement assembly for the Sn/Cu and the Cu plated holes are summarized in Table 2, together with the retention forces after assembly. The retention forces for the Sn/Cu and the Cu plated holes, which were the maximum loads observed during the push-out testing, were 57.1 and 43.0 N, respectively, and it was experimentally found that the retention forces after assembly
Fig. 6  Load-displacement relationships of the press-fit pin for the Sn/Cu and Cu plated holes

Table 2  Maximum loads during assembly, together with the retention forces

| Through hole (0.94mm diameter) | Maximum load (N) | Retention force (N) |
|--------------------------------|------------------|---------------------|
| Sn/Cu plated hole              | 91.4             | 57.1                |
| Cu plated hole                 | 78.9             | 43.0                |

were close to the loads at the end of the load-displacement relationships for the pin. The maximum load during the press-fit assembly in the Sn/Cu plated hole was larger than that in the Cu plated hole. Also, the retention force between the pin and the Sn/Cu plated hole was larger than that for the Cu plated hole. The differences in the maximum load during assembly and the retention force between the Sn/Cu and the Cu plated holes were brought by the difference in the frictional behavior between the pins and the plated holes.

4.2 Numerical results

Nodal reactions of the pin contacting with the plated hole, $f$, are shown by vector representations in Fig. 7 (a)–(c), for pin displacement values of 0.3, 1.2 and 2.0 mm, respectively. At the initial stages of the assembly, the contacting region between the pin and the surface of the plated hole moved toward the deeper side from the front surface of the PCB with increasing the pin displacement. At the end of assembly, as shown in Fig. 7 (c), the contacting region was formed in two positions, one located near the front surface and the other in the vicinity of the back surface of the PCB. The contacting angle between the press-fit pin and the plated hole, $\alpha$, became smaller with increasing displacement of the pin, and, at the end of the assembly, the direction of $f$ approached the $z$-direction.

5. Discussions

5.1 Coefficient of friction

For determining the coefficient of friction of a press-fit pin in thin plating during assembly, let us consider a model shown in Fig. 8. Here, if we assume that the coefficient of friction between the pin and the plating, $\mu$, is
constant in the contacting region at a state during assembly, the load, $F$, during the insertion of the press-fit pin into the plated through hole is given by

$$F = F_1 + \mu P,$$

where $F_1$ is the $x$-component of the reaction of the pin contacting with the plating, and $P$ the equivalent normal force working on the pin in the contacting region. The terms $F_1$ and $P$ are given by

$$F_1 = \Sigma \sin \alpha \cdot |f|,$$

and

$$P = \Sigma \cos \alpha \cdot |f|.$$

The symbol $\Sigma$ refers to the sum of the contributions of all the nodes on the plating surface. From Eq. (1), we obtain $\mu$ as

$$\mu = (F - F_1)/P.$$

Also, the average pressure working on the plating surface in the region where the pin was contacting the plated hole is given by

$$p = P/A,$$

where $A$ is the apparent contacting area. The values of $A$ determined from numerical analysis without considering the surface roughness of the pin and the plated hole will not be identical with the real contacting area between the pin and the plating surface.

The relationships between $\mu$ and $p$ for the Sn/Cu and Cu plated holes are shown in Fig. 9. Here, when determining the values of $\mu$, the values of $f$ for the Sn/Cu plated hole were the same as those for the Cu plated hole. From the numerical results, the values of $A$ were found to be as small as under 0.5 mm$^2$, and the values of $\mu$ determined in this study were interpreted as the average values of the friction coefficients in the small contacting region at a state during assembly. Figure 9 clearly shows that the values of $\mu$ for the Sn/Cu plated hole were always greater than those for the Cu plated hole. The press-fit pin was coated with Sn plate, and this made a common metal contact with the Sn/Cu plated hole. It is well known that the such common metal contact takes a higher value of $\mu$ due to adhesion in the contacting region. According to adhesion theory, the frictional force per unit area is proportional to the real contacting region over an area, $a_r$. In Fig. 9, the values of $\mu$ for the Cu plated hole were almost constant at 0.26 in the $p$ range during assembly. From this fact, it was concluded that the $a_r$ was proportional to $p$ in the case of the Cu plated hole. On the other hand, the values of $\mu$ for the Sn/Cu plated hole decreased with increasing $p$, and were given by $\mu = -0.29 \times 10^{-3} p + 0.49$, where $p$ was in MPa. This fact suggested a nonlinearly between $p$ and $a_r$ for the Sn/Cu plated hole. In the case of the Sn/Cu plated hole, the values of $a_r$ were already almost saturated in the low $p$ zone because Sn is very soft. In this case, the values of $a_r$ bore little relationship to $p$, and the friction force per area at the contacting region was not much increased by the additional $p$ value. Thus the values of $\mu$ for the Sn/Cu plated hole in the high $p$ zone became smaller than those in the low $p$ zone.

5.2 Prediction of the load-displacement relationships

In order to check the validity of the determined relationships between $\mu$ and $p$ for the Sn/Cu and Cu plated holes, we considered the different press-fit assemblies, where the same press-fit pins were inserted into the plated through holes with a diameter of $1.01 \pm 0.03$ mm, and the load-displacement relationships of the pin were predicted. The load-displacement relationships for the Sn/Cu and the Cu plated holes predicted from the numerical results and the model shown in Fig. 8 are shown in Fig. 10 (a) and (b), together with the experimental results. The predicted load-displacement relationships of the pin that were obtained...
numerically are in good agreement with the experimental ones. It was experimentally confirmed that the relationships between \( \mu \) and \( p \), approximated above, were valid for the cases of both plated hole types. The behavior of \( F_1 \) and \( \mu P \) are also shown in Fig. 10. The values of \( \mu P \) were always greater than those of \( F_1 \) for both plated holes, and this fact indicated that much of the load was spent on the friction between the press-fit pin and the plated through holes during assembly.

From the loads at the end of the reproduced load-displacement relationships, the retention forces of the pin for the Sn/Cu and the Cu plated holes having the diameter of 1.01 mm were predicted to be 62.0 and 45.5 N, respectively. The experimental values of the retention forces for the Sn/Cu and the Cu plated holes obtained by the push-out testing were 59.6 and 44.2 N, respectively, and the predicted retention forces were in good agreement with the experimental ones.

6. Conclusions

In conclusion, we proposed a methodology to determine the friction coefficient of the press-fit pin in thin plating. A type of compliant press-fit pin was assembled into two types of plated through holes on printed circuit boards, one was Sn/Cu plating and the other merely Cu plating, and the load-displacement relationships of the pin during assembly were recorded. It was experimentally confirmed that the retention forces working between the pin and the plated holes corresponded to the loads at the end of the load-displacement relationships of the pin. The nodal reactions of the pin contacting with the plated hole during assembly were obtained from the three-dimensional finite element analysis, without considering the friction between the pin and the plating surface. By using the load-displacement relationships of the pin obtained experimentally, together with the numerical results, the coefficients of friction of the pins on thin plating were successfully determined. The friction coefficient of the pin on the Sn/Cu plating was a function of the average pressure imparted to the plated surface where the pin was in contact, whilst that on the Cu plating was the almost constant during assembly. Because the Sn/Cu plating formed the common metal contact with the pin used, the friction coefficient for the Sn/Cu plating was higher than that for the Cu plating during assembly, due to adhesion on the contacting region. Using the determined friction coefficients, we were able to reproduce the load-displacement relationships for the different assemblies of the pin into the Sn/Cu and the Cu plated holes. The predicted load-displacement relationships of the pin were in good agreement with the experimental results, and the retention forces between the pin and the plated holes were also predictable.

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