Sliding speed effect in press-fit connection using Finite Element Analysis

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Abstract. Solderless press-fit contacts in power module packages are now gaining more attention in the automotive industry especially in hybrid electric vehicles because of the Restriction of Hazardous Substances (RoHS) directive to eliminate lead-based connections. The production of press-fit assembly is also faster, more convenient, safer, and cheaper than soldered connections. In this paper, the effect of insertion speed of pin to the press-in force as well as the pull-out speed to the retention force was investigated using finite element analysis. An eye-of-the-needle (EON) shape compliant pin with general dimensions was adapted and a transient structural analysis in ANSYS mechanical was used to add and vary the speed of the press-fit pin geometry. Four simulations were conducted with different speeds. The results obtained by FEA show that the speed when kept at constant has no significant effect both on the press-in and retention force. However, when the speed changes due to acceleration, the press-in and pull-out force are both affected.

1. Introduction

Press-fit technology is now commonly used in electronic packages because of its connection reliability [1]. It also becomes even more popular in the power modules that are used for power conversion in the area of renewable energies and automotive industries especially in hybrid electric vehicles which are subject to various outdoor conditions [2]. Press-fit contacts were first introduced in the telecommunication industry in the late 1960’s [3] but are now gaining more attention because of the Restriction of Hazardous Substances or RoHS directive to eliminate lead-based connections in electronic package especially in the automotive industry as the demand for solderless connections in hybrid power trains continues to increase [4].

A press-fit contact is achieved when a pin is inserted into a plated through hole (PTH) of the printed circuit board (PCB). Figure 1 shows a typical Eye-of-the-Needle (EON) press-fit pin with its initial and final position on the PCB. The compliant pin (the elastic portion) deforms during the insertion process and creates a contact force against the hole. Since the press-fit pin has a slightly larger cross-sectional dimension than the hole, interference occurs and generates a gas-tight metal to metal contact between the press-fit pin and the plated through hole [5]. When compared to a soldered connection, a solderless
press-fit assembly process is faster, more convenient, and safer [1]. In addition, since a press-fit connection is a solderless process, this reduces the production cost because the soldering materials and equipment like robots are eliminated and no additional cleaning step for soldering flux leftovers [6]. This makes a solderless press-fit pin connection cheaper than a soldered connection.

Figure 1. Press-fit process [5].

One specification of the press-fit process that needs to conform with the IEC 60352-5 standard is the press-in and retention force. According to Ring and Alt [4], these forces were affected mainly by these physical parameters, namely, the shape of the pin, the material of pin (core material and plating), diameter and homogeneity of PCB plated through hole (PTH), thickness of PCB and amount of laminate layers, material and the thickness of PTH plating, and press-in speed and temperature. In this study, a finite element method (FEM) is employed to study the effect of insertion and pull-out speed on the press-in and retention force of the press-fit assembly, respectively.

Finite element method has already been used by several researchers to study the behavior of the press-fit pin and PCB assembly. Yang et al. [1] developed a 3D finite element model to simulate the insertion process of press-fit assembly especially to study by simulation the possible failures of the press-fit pin during the laser soldering process. Riedel et al. [2] also used a 3D FEM as an additional tool to validate the measurement of electric current distribution within the pin-via-trace geometry. Another 3D FEA was performed by Ring and Alt [4] to examine the surface strain gradient on the PCB during the press-fit insertion process and was compared to two different sensor technologies. While Tohmyoh et al. [7] used a 3D FEA with an experimental set-up to determine the coefficient of friction of the compliant pins in the plated through holes (PTH) of PCB. Moreover, a very recent paper by Wang and Xu [8] exhaustedly used FE simulation to obtain and analyze the mechanical behaviors (which include mechanical stress, thermal stress, and contact force) of a typical eye-of-the-needle (EON) press-fit pin. However, no prior works yet have been published on developing a FE model to investigate the effect of sliding velocity on the press-in and retention force of press-fit pin.

This study aims to determine if any changes on the sliding speed during the press-in and pull-out process could significantly affect the magnitude of press-in and pull-out force of the press-fit pin, respectively using finite element analysis.

2. Finite Element Analysis
The basic principle of press-fit contact is that a terminal pin is inserted into the through hole of a printed circuit board (PCB). There are two types of press-fit pin terminals; the compliant pin which has the elastic behavior and the solid pin which is the terminal at the other end of the pin and is usually the one attached to the power module side [9]. In this paper, only the compliant pin having the elastic behavior is the focus and the press-fit pin being defined here.

Since the press-fit pins are injected into the PCB hole using assembly jigs, the amount of force to press-in the pins should be limited only to a certain degree to achieve reliable connections. The maximum force needed to press-in the pin into the plated through hole of PCB is called the press-in
force, while the minimum force needed to pull-out the press-fit pin from the hole is called the retention force. Both these two forces should be within the standard value specified by the IEC 60352-5 [10]. The said standard also specified a recommended sliding speed during the press-fit assembly as the speed may also influence the quality of press-fit connections [5].

When installing press-fit connectors, press jigs or servo systems are designed for precision control of speed, position, and pressing forces [11]. Tomhyoh et al. [7, 12] used a constant speed of 0.833 mm/s to analyze the press-fit connection. While Ring and Alt [4] used a constant speed of 12 mm/min or 0.2 mm/s in recording the press-in force. However, no prior study yet recording the press-in force and the retention force while varying the sliding speed. Moreover, the recommended sliding speed by IEC 60532-5 standard is a range from 25 mm/min to 50 mm/min (0.417 mm/s to 0.833 mm/s) [5]. To verify the influence of sliding speed on the press-in and retention force, a finite element analysis of the press-fit assembly was modelled in this study.

**Figure 2** illustrates the applied and reaction forces during contact of pin and plated through hole surfaces. During the press-in or insertion process, a load $F$ is applied in $y$-direction. The plated hole in PCB is deformed and exerted a force to oppose the applied force by the press-fit pin. Using Newton’s second law of motion, the summation of forces in $y$-axis is given by

$$\sum F_y = ma$$

rearranging, gets

$$F = R_y + \mu P + ma$$

where $F$ is the load applied to insert the press-fit pin, $R_y$ is the $y$-component of reaction force in contact region, $P$ is the normal force working on the pin in $x$-axis with $\mu$ as the assumed friction coefficient, $m$ is the mass, and $a$ is the acceleration of the pin in $y$-direction.

Due to the slight deformation in plated through hole during assembly, $R_y$ and $P$ are given by

$$R_y = \sum \sin \alpha \cdot |f|$$

and

$$P = \sum \cos \alpha \cdot |f|$$

where the symbol $\sum$ is just referring to the summation of all nodes contribution on the contacting surface [12]. Notice that from equation (1), the required press-in force $F$ increases when the acceleration $a$ increases.

![Figure 2. Free body diagram of press-fit contact region.](image)

Moreover, when the acceleration is zero ($a = 0$), that is when the velocity is constant, the last term in equation (1) will be zero. That is,

$$F = R_y + \mu P$$

(4)
Hence, as long as the velocity is constant throughout the insertion process, its magnitude does not affect the magnitude of press-in force.

For the pull-out force, the direction of load $F$ would be in opposite. Thus,

$$F = -R_y + \mu P + ma$$  \hspace{1cm} (5)

A transient structural analysis in ANSYS Workbench was implemented on the FE model of the press-fit assembly to validate how the sliding speed influences the press-in and retention force. The geometric model of the press-fit assembly is shown in Figure 3. The dimensions of the EON compliant pin were taken from [8]. The 1.6 mm thickness of the PCB is a standard thickness and the hole dimensions, as well as the plated through hole were selected as general dimensions.

The parts of the press-fit model are made of three different materials, phosphor bronze, copper, and epoxy resin [7]. Their mechanical properties are listed in Table 1. Since some areas on the contact surface during the press-fit process undergo plastic deformations, a plastic model is adopted which is a Bilinear Isotropic Hardening model [13].

Table 2 summarizes the contact definition of the press-fit contact during the press-in and pull-out process. The assumed value of the friction coefficient was 0.2. Some values used for friction coefficient may be more than 0.2 [8], but to avoid convergence issues and no need to increase the mesh quality, a value not more than 0.2 was selected. The contact between the PCB hole and the PTH surface was bonded. Moreover, Figure 4 shows the load and boundary conditions of the model. A symmetry region was added to lower the number of mesh elements and so the computational time. The total number of nodes was 51577 with 14786 elements. Finer mesh elements were added to the contact surfaces with a minimum element size of 0.03 mm. Figure 5 shows the meshing of the model.

Table 1. Mechanical properties of three parts of press-fit assembly [8].

| Material                  | Young’s modulus (MPa) | Poisson’s ratio | Yield strength (MPa) | Tangential modulus (MPa) |
|---------------------------|-----------------------|-----------------|----------------------|-------------------------|
| EON compliant pin (phosphor bronze) | 77500 | 0.3 | 731 | 103 |
| PTH (copper)              | 21000 | 0.3 | 305 | 200 |
| PCB (epoxy resin)         | 10800 | 0.3 | 151 | 7930 |

Table 2. Contact definition.

| Contact model                  | Surface to surface              |
|-------------------------------|---------------------------------|
| Type                          | Frictional                     |
| Coefficient of friction       | 0.2                             |
| Offset                        | Set manually on the geometry    |
| Behavior and formulation      | Program controlled              |
| Contact element               | PTH contact surface             |
| Target element                | Compliant pin contact surface   |

Frictionless supports were added as constraints to the four sides of the PCB. Another frictionless support was added to the bottom of the PCB by which the reaction force exerted by the press-fit pin was taken. There was no fixed support added since the frictionless supports kept the PCB from moving already. Frictionless supports were also added to the symmetry plane to restrict it from deforming in that region. For the press-in process, the compliant pin was inserted into the PCB by displacing the pin 2.5 mm from its initial position. While for the pull-out process, the pin was ejected from the PCB and displaced to its original position. Finally, a velocity was added in the direction of the compliant pin.
3. Results and discussion

The FE simulation of the press-fit assembly is based on the parameters shown in table 3. Press-in and retention forces were obtained by getting the component of reaction force in the direction of pin’s displacement at the frictionless support in the bottom surface of the PCB.

The sliding speed, both for the press-in and pull-out process, was varied accordingly. For the first three simulations, the speeds were kept at constant throughout the simulation. The lowest speed tested was 0.2 mm/s to account for the speeds slightly lower than the recommended speed by IEC 60352-5 standard. Next, was the 20 mm/s speed which is far higher than the recommended speed. The obtained forces between 0.2 and 20 mm/s speed did not significantly differ from each other so another
significantly higher speed was tested which is 50 mm/s to confirm the results. The force vs. displacement curves are shown in Figure 6. The press-in and retention force curves of the first three simulations were almost identical except for the slight difference between their maximum retention forces. The obtained maximum press-in force in this study was 15% higher than the experimental result by Wang and Xu [8]. While the maximum pull-out force was 20% lower than the experimental value.

Table 3. Maximum press-in and retention force obtained from FEA.

| Maximum force (N) | 0.2 mm/s | 20 mm/s | 50 mm/s | (0.5 – 50) mm/s |
|-------------------|----------|---------|---------|-----------------|
| Press-in force    | 56.18    | 56.181  | 56.181  | 54.938          |
| Retention force   | 30.932   | 30.15   | 31.261  | 31.815          |

Figure 6. Relationship between (a) press-in force and displacement (b) retention force and displacement.

To see the outcome when the process is not at a constant speed, the fourth case was added where the speed was varied from 0.5 mm/s to 50 mm/s. Figure 7 shows the velocity plot for this simulation. This time, acceleration or deceleration was happening. The contact of the pin and PTH surface begins at around 0.5 mm from its initial position so an acceleration was added after the 0.5 mm displacement to see if the acceleration affects the press-in force. Then, it decelerates before a full stop.

For the pull-out speed, an acceleration was added from 0 to 0.5 mm displacement and then a deceleration for the rest. The results show that the force-displacement curves of both the press-in and pull-out process were affected when an acceleration is added. The maximum values of forces were also slightly affected by the addition of acceleration. It can be observed in Figure 6b that the pull-out force...
from 0 to 0.5 mm displacement is higher compared to the curve with constant speed, and then lower when deceleration begins. For the press-in force, an offset can be noticed from the curve with constant speed in Figure 6a. The maximum press-in force in the case with acceleration was lower than the maximum press-in force with constant speed.

Moreover, Figure 8 shows a sample of the final position of the press-fit assembly obtained from the simulation displaying the deformations. It shows the deformations on the barrel’s surface and on the compliant pin. During the contact, only the corners of the compliant pin are in contact with the PTH and not the whole surface of the pin as can be noticed from the top view of the figure. Thus, an electrical resistance may increase due to the presence of contact gap. Adding larger fillet radius on the pin’s corner may eliminate this gap and may improve the connection reliability.

4. Conclusion
The effect of the sliding speed on the press-in forces and retention force was studied based on finite element analysis. The simulation was tested in different constant sliding speeds, 0.2 mm/s, 20 mm/s, and 50 mm/s. A simulation also having a changing speed from 0.5 to 50 mm/s instead of a constant speed was conducted. The force vs. displacement curves were plotted and the maximum forces were recorded. The maximum press-in force at constant sliding speed was 56.18 N but when acceleration was added, the maximum press-in force was 54.94 N. For pull-out force, the maximum force was 30.15 N and 31.82 N for constant speed and for the case with acceleration, respectively. Based on the FEA results and as predicted theoretically, it can be concluded that the acceleration affects the press-in and pull-out force of the press-fit pin but not when the sliding speed is kept at constant. Moreover, any changes on the speed during press-in assembly may affect the reliability of connections such as when bending of press-fit pins occurs due to misalignment and may provide higher stresses on contact surfaces which may be considered for further studies.
Acknowledgment
The authors would like to acknowledge the Philippine’s Department of Science and Technology with the Collaborative Research and Development to Leverage Philippine Economy (DOST-CRADLE) program under the Philippine Council for Industry, Energy and Emerging Technology Research and Development (PCIEERD) with project No. 8897, 2020, for the assistance and funding this research. The authors would also like to recognize the DOST-ERDT consortium for the scholarship program awarded to the authors in taking up Graduate study.

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