Analysis of the effects of geometry on the press fit application in automotive power modules

A T Ubando$^{1,2}$, J Gonzaga$^{1,2}$, E Arriola$^{1,2}$, R L Moran$^{1,2}$, N R E Lim$^{1,2}$, J P Mercado$^{1,2}$, A Conversion$^{1,2}$, D Belarmino$^{1,2}$

$^1$Mechanical Engineering Department, De La Salle University, 2401 Taft Avenue, 1004 Manila, Philippines
$^2$Thermomechanical Analysis Laboratory, De La Salle University – Manila, Laguna Campus, LTI Spine Road, Laguna Blvd, Biñan, Laguna, Philippines

aristotle.ubando@dlsu.edu.ph

Abstract. Semiconductors and electronics have been found to have an increasing use in automobile design. One key component of an automobile is the power module, which is a high voltage component that finds itself in extreme operating conditions. Due to this condition, the power module demands for highly effective terminal connections that can withstand the extreme operating condition specifically on the terminals that will connect the power module to the automobile system. Press fit technology has been a solution for cheap and reliable methods of creating interconnections since the 1980s; however, necessary innovations exist for more environmental design, and increase demand in quality and quantity. Press fits are simple, force-fitting connectors that allow permanent bonds without solder or adhesive bonding and a shortened process time. This research presents a unique methodology on the evaluation of the effects of the geometry to the insertion force and retention force using finite element analysis. The result showed that the geometry of the pin in a press fit pin configuration has a significant effect on the insertion force, retention force, as well as in the equivalent stress.

1. Introduction

As electronics are now fundamental to the modern automobile, semiconductor packages are put under harsh operating conditions of the vehicle and local climate. Furthermore, miniaturization and the demand for greater functionality drive the demand for denser interconnections in electronics. The power module is a primary component, exposed to 150 Celsius or higher ambient operating temperature and high vibrations forces [1]. This all generates harsh thermal cycling for their interconnection. A white paper by Lynch & Longford [1] outlines the ambient temperatures of hood and near engine temperature requirements for power module assemblies.

Press fit technology is a 'force fitting' interconnection solution that has been in use in automobile power modules and electronics since the 1980s. 'Force fitting' means that two or more components are pressed into place and locked together via the plastic deformation that occurs as components are pressed together [2]. Press fit pins were originally in use for telecommunication electronics in the 1960s[3] and were only introduced later to automotive design.
Table 1. OEM automotive temperature classes by [1] which highlighted the under hood and near engine ambient temperature ranges.

| Temperature Class | Temperature Range | SAE Temperature Classifications |
|-------------------|-------------------|---------------------------------|
| Low               | High              | Class | Ambient Temp.   |
| 1                 | +40 to +85°C      | 1     | -40 to +85°C    |
| 2                 | +40 to +100°C     | 2     | -40 to +125°C   |
| 3                 | -40°C +100°C      | 3     | -40 to +150°C   |
| 4                 | +105°C +125°C     | 4     | -40 to +175°C   |

While our research concentrates on the compliant press fit pin inserted in a solid press-in zone, another type exists that is a solid pin for a compliant press-in zone [4]. Compliant pins enjoy more favored use compared to solid pins, due to lower insertion force, elimination of damage to the plated through holes (PTH) insertion zone, and more reliable signal [5]. The compliant, press fit pins gain the best economy compared to most electronic joints and possess an ease in assembly, repair, and interchangeability. Removing the soldering process eliminates the thermal cycling, contaminant and heat flux, and environmental impact associated with it [6]. These designs are fitted into the PTH of a PCB, which vary in sizes up to 0.8 mm. The FR-4 plate finishes of a PCB are most commonly Tin, Silver, Gold, and OSP, and have a thickness of 1.57 mm or higher. In the press-in zones, plating can be reduced to 1 micron, while the allowable contact resistance in any connection may only go as high as 0.5 mW [4].

A white paper by Lynch & Longford [1] presents a press fit design in 0.64 mm and 0.8 mm thickness. This experimented with CuSn5 (15% IACS), 7025 CuNiSi (40% IACS), and two special brass alloys with 30% and 80% IACS; the interchanging of materials allows the design to survive in either 125 or 150 Celsius operating conditions.

![Figure 1](image1.png)  
**Figure 1.** (a.) solid press-fit pin with compliant PTH versus (b.) compliant press-fit pin with solid PTH [6]

High contact pressure from macroscopic 'squeezing' forces are concentrated in localized areas, allowing press-fit pins to deform into the press-in zones. Recrystallizing of free electrons occur on the contact metal surfaces, creating a cold weld phenomenon and increasing bonding forces. This
phenomenon is more prominent in Tin plated surfaces, hence the use of Tin-lead (SnPb) surface finishes for the compliant pins and PTH [6]. Tin-lead finishes are also able to effectively reduce contact resistance down to 0.1 m\(\Omega\) while increasing mechanical stability. These innovations were able to reduce the necessary retention force below 20 Newtons [5]. However, the push for lead-free alternatives in electronic components poses a challenge in creating metal finishes that can possess a similar efficiency.

Chou and Hilty [6] conducted a design of experiment (DOE) study to reduce the retention force required for lead-free, compliant press fit pins. The research found that the hole size has a linear inverse relationship with insertion force while finish of the compliant, press-fit pins has a direct relationship with retention force. The minimum radius a metal contact is able to carry current is greater than 10 micrometers [2], meaning that bumps in metal surfaces will vary in their ability to carry a current, affecting overall resistance of a metal to metal contact. The retention force, typically between -20 and 40 Newtons, is important for the stability of the press-fit pin while insertion force is necessary to guide pin application. [1, 6]

![Figure 2. Insertion of compliant press-fit pin into solid PTH [1]](image)

Corrosion, organic wastes, and contamination leads to contact issues into the press-fit pin technology. Most problems arise from corrosion; fusing surfaces of noble metals are known to reduce corrosive effects. Cracks and signal disruption will still occur due to deformation in the material. Stotze et al. [2] explores non-destructive reliability tests and analysis of press-fit technology, for power modules in climactic conditions. The author also explores the fritting phenomenon, where corrosion build up is burnt away by low voltage. Finite Element Analysis (FEA) was used by Fellner et al.[7] to explore the stability and connection reliability of molded interconnection devices (MID) press-fit pins for 3-dimensional PCB substrates. Their model was able to describe the behavior of the coefficient of friction, assisted with empirical data. Their model predicts force-displacement curves, retention forces, and mechanical and thermal stresses of the pins.

This paper uses FEA to create a model to predict necessary press-in forces and contact/sliding frictional forces that affect retention forces in a compliant, press fit pin.

2. Methodology
The determination of the different forces and stresses in a press fit connection was conducted using finite element analysis. Finite element analysis (FEA) is used to determine the distribution of stress in a complex geometry [8]. As discussed by Ogrodnik [9], finite element analysis is fully accepted for simulation of experimentations. The predictions result of FEA for strains, warpage, stress, etc. are widely acceptable as predictions of reality. The application of FEA is suitable for drop test analysis due to its superior capability of analyzing diversified problems with complicated geometry [10]. FEA utilizes the piecewise approximation wherein the geometry is divided into smaller body (discrete subregions) called finite elements. Each of these elements is represented by a set of nodes which are
controlled by a set of partial differential equations with respect to its physical disciplines [10]. The whole analysis is carried out flowing the methodological framework of the study as shown in Figure 3.

**Figure 3. Methodological Framework**

The geometry evaluated came from the commercially available pins [11]. The geometry selected was created using Solidworks 2020 under the license of De La Salle University. The mesh was set to fine setting for a more accurate result. Specifically, meshing focuses on the refinement around the contact area between the pin and the plated through hole. A refined mesh strategy, together with a target minimum number of elements within the targeted contact region, was applied to ensure the accuracy of results. The simulation platform used in the analysis was ANSYS Workbench 2020 R1 licensed under the De La Salle University in the Thermomechanical Analysis Laboratory while the finite element analysis was based on the study of Wu et al. [12]. The computer utilized for the simulation is equipped with Xeon Gold Processor with 20 cores and 128 GB RAM.

**Table 2. Different geometry used in the simulation.**

| Type of geometry | Illustration |
|------------------|--------------|
| Eye of Needle    | ![Eye of Needle](image) |
| M-Shape          | ![M-Shape](image)   |
| Multi-Spring     | ![Multi-Spring](image) |
| Barrel           | ![Barrel](image)    |
The main assumption on the simulation was the starting point which was the pin was already inserted in the plated through hole. The analysis starts on the pull out of the pin in the plated through hole. The retention force, insertion force, and equivalent force will be determined and evaluated on each geometry. Different types of geometry used in the evaluation were shown in Table 2. A frictional contact condition was applied, where the target was the barrel PTH. A coefficient of friction of 0.2 was applied for these contact conditions.

The thickness of the pin used in all geometry is 25 μm while the barrel has the thickness of 1.6 mm. The properties of the materials used in the simulation was adopted from the experimentation of Tohmyoh et al [13] which is phosphor for the pins and copper for the barrel. Table 3 summarized the material properties of both components.

| Table 3. Material properties of the components used in the simulation. |
|---------------------------------------------------------------|
| Property                      | Pins (Phosphor) | Barrel (Copper) |
|--------------------------------|----------------|-----------------|
| Yield stress (MPa)             | 731            | 305             |
| Poisson's ratio                | 0.30           | 0.35            |
| Young's modulus (GPa)          | 77.5           | 21.0            |
| Hardening modules (MPa)        | 103            | 200             |

A mesh independence test was conducted to control the quality and efficiency of the simulation in consideration of the computational time and accuracy of the mesh are both satisfactory. The simulation time took approximately 40 mins per geometry.

The model was configured to identify the effects of the different geometry on the insertion force, retention force, and in the equivalent stress in the press fit set up. Simulation overview is illustrated in Figure 4.

![Figure 4. Simulation overview](image)

Each pin geometry was initially inserted in the barrel then the simulation model will identify the insertion force, retention force, and equivalent stress of the press fit set up to evaluate the effect of the geometry while keeping the materials constant and coefficient of friction at 0.2.

3. Results and discussion
The simulation results showed significant impact of the geometry with respect to the insertion force, retention force, and on the equivalent force of the press fit configuration. The simulation output indicates that the multi-spring pin needed the highest force (41.1 N) in terms of insertion while the eye of the needle geometry requires the least force (6.91 N) (Figure 5). This pertains to the force required to assemble the press fit configuration [14]. With the results obtained, the barrel assumes the frictional force and the pressure on the press fit configuration which leads to a three-dimensional stress state.
occurrence on the barrel. During the insertion, the stress due to compression exists on the radial direction of the barrel, while the tensile stress occurs in an axial direction on the circumference. Considering that the copper barrel has high ductility, the von mises stress can be used as the indicator for parametrical study on failure analysis.

![Insertion Force Diagram](image)

**Figure 5.** Insertion force comparison of the three geometry

The retention force can be defined as the maximum load exerted in the pull-out simulation. This force is governed by the normal force acting in between the through hole and the pin as well as the coefficient of friction acting on the contact region [15]. The results have shown that the M-Shape pin holds the highest retention force with 257.3 newtons compared to Multi-spring (93.3 N) and Eye of needle geometry (10.7 N) (**Figure 6**).

![Retention Force Diagram](image)

**Figure 6.** Retention force comparison of the three geometry.

And lastly, the M-shape yielded the most equivalent stress with 370 MPa followed by the multi-spring (138.3 MPa) and eye of the needle (48.1 MPa) (**Figure 7**). High retention force is preferred on the application of press fit. This force ensures the reliability of the connections of the semiconductor devices on the electronic control units which are crucial in automobile operation.
4. Conclusion
The study focuses on the investigation of the geometry of the pins in the press fit configuration and how it affects the forces involved such as insertion force, retention force and equivalent stress. The results had shown that the geometry of the pin in a press fit pin configuration has a significant effect on the insertion force, retention force, as well as in the equivalent stress. It is also noteworthy that the insertion force does not have a direct relationship with the retention force. It can be observed in the case of the multi-spring and in the M-shape pin where the multi-spring resulted into a 12% higher insertion force but yielded on a significantly 93% lower retention force compared to the M-Shape. In this study, out of the three geometries, the M-shape pin showed the best parameter with lower insertion force needed yet, it has the highest retention force for the press fit pin configuration.

The authors recommend further investigation on the relationship of the insertion force and retention force as well as the factors that affect these forces such as contact surface area and temperature.

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 project no. 08897 under the Philippine Council for Industry, Energy and Emerging Technology Research and Development (PCIEERD) project and Department of Science and Technology - Engineering Research and Development for Technology (DOST-ERDT) for the assistance and funding of this research.

References
[1] Lynch J and Longford A, 2009 Adapting press-fit connection technology for electronic modules in harsh environments (Interplex Industries, Inc.)
[2] Stolze T, Thoben M, Koch M and Severin R 2015 Reliability of PressFIT connections (Infineon Technologies, Warstein)
[3] Corman N, Myers M and Copper C 2003 Friction behavior of press-fit applications: test apparatus and methodology Forty-Ninth IEEE Holm Conf. on Electrical Contacts (Harrisburg, PA, USA, 2003: Tyco Electronics Technology)
[4] "Press-Fit Connections for the Automotive Industry (Catalog 1654403-1)." (TE Connectivity Germany) (accessed.
[5] Goel R 1981 An analysis of press-fit technology Electronic Components Conference (Atlanta Georgia)
[6] Chou G J S and Hilty R D 2003 Effects of lead-free surface finishes on press-fit connections The IPC Annual Meeting 2003 (Minneapolis, MN, USA)
[7] Fellner T, Zukowski E and Wilde J 2009 Modelling of process and reliability of press-fit interconnections Int. Conf on Thermal, Mechanical and Multiphysics Simulation and Experiments in Micro-Electronics and Micro-Systems (Freiburg, Germany)

[8] Mills N J 2007 Chapter 6 - Finite element modelling of foam deformation Polymer Foams Handbook (N. J. Mills Ed. Oxford: Butterworth-Heinemann) pp 115-145.

[9] Ogrodnik P 2020 Chapter 10 - Evaluation (validation and verification) Medical Device Design (Second Edition) (P. Ogrodnik Ed.: Academic Press) pp 317-375.

[10] Bi Z 2018 Chapter 1 - Overview of finite element analysis," in Finite Element Analysis Applications (Z. Bi Ed.: Academic Press) pp 1-29.

[11] F. C. LTD. Appearances and Shapes of Press-Fit Terminals https://www.finecs.co.jp/en/knowledge/press_fit.html?fbclid=IwAR28fMPQDxmEfchu5aRomzABcleLcZ7MTrUM8xxRkP9HBYZKpXlBb5qqkk (accessed December 1, 2020).

[12] Wu B-H et al. 2018 Study on the contact performance of electronic EON connectors under axial vibration IEEE Transactions on Components, Packaging and Manufacturing Technology 8(12) pp 2090-2097

[13] Tohmyoh H, Yamanobe K, Saka M, Utsunomiya J, Nakamura T and Nakano Y 2008 Analysis of solderless press-fit interconnections during the assembly process Journal of Electronic Packaging 130(3)

[14] Kim S-Y, He B, Shim C-S and Kim D 2013 An experimental and numerical study on the interference-fit pin installation process for cross-ply glass fiber reinforced plastics (GFRP)," Composites Part B: Engineering 54 pp 153-162 2013/11/01/ 2013, doi: https://doi.org/10.1016/j.compositesb.2013.05.006.

[15] Palaniappan A, Li L and Lee T-K 2018 Impact of press-fit connector pin microstructure elastic response to PCB through-hole Cu wall interface long-term contact reliability 2018 IEEE 20th Electronics Packaging Technology Conference (EPTC) (IEEE) pp 890-893.