TOWARD LEAD-FREE COMPLIANT PIN CONNECTIONS

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ABSTRACT

Although compliant pin (or press-fit) connector systems may be exempted from the WEEE and RoHS directives, OEM's are still continuing their demands for the lead-free products. The current study has conducted statistical analyses on the multi-level full factorial DOEs from new data and a previous investigation on lead-free compliant pin connections. The DOE data were from the mechanical characterization of the lead-free connection using eye-of-the-needle (EON) compliant pin. The DOEs include the variables: PTH finish (HASL, galvanic Au, OSP, immersion Sn, immersion Au, and immersion Ag), PTH size, compliant pin finish (bright tin-lead, bright tin, matte tin, and gold) over nickel, pin stock thickness, and installation/repair. The effects from these variables and their interactions have been analyzed to assess the impact to the lead-free EON compliant pin connections. The PTHs with inserted pins were also cross-sectioned and evaluated to assess the deformation and distortion by the compliant pins.

Another key issue with press-fit connector systems is concern about the formation of tin whiskers. Since complaint pin products employ significant compressive stress to the tin plating, tin whisker growth can be accelerated. The results summarized here include the tin whisker testing as per the iNEMI tin whisker test methods on matte tin over nickel, bright tin over nickel as well as bright tin-lead over nickel as applied to compliant pin connector systems.

Key words: lead-free, compliant pin, press-fit, connector, tin whisker.

INTRODUCTION

Compliant pin (or press-fit) connection is an interconnect technology that mechanically and electrically joins a connector to a printed circuit board (PCB). The connector is not soldered to the PCB and is mechanically separable for easy repair or replacement. For decades, this solderless connection has proven to be reliable and tin-lead alloys have been used as the primary surface finishes for both PCB and compliant pin in the connection. However, with the rapid approach of the Waste Electrical and Electronic Equipment (WEEE) and Restriction on Hazardous Substances (RoHS) directives restricting the used of lead and its compounds, manufacturers are working very hard for a smooth transition from tin-lead to lead-free both in component manufacturing and PCB assembly. The conversion of tin-lead to lead-free coatings has resulted in significant challenges and changes in material, design, and manufacturing processes for the components and assembly.

Although the compliant pin connector systems may be exempted from the WEEE and RoHS directives as mentioned in a recent unofficial note[1] in the WEEE and RoHS TAC meeting, many OEMs (original equipment manufacturers) are still continuing their demand for lead-free products. To address the impacts of lead-free conversion on the products, several studies[2-5] have been conducted in the past few years to evaluate and investigate the lead-free compliant pin connections. Using the lead-free compliant pin technology, stable electrical connection has been demonstrated in two studies[2,3] even under mechanical, thermal, climatic, and atmospheric corrosion conditions (i.e., vibration, rapid change of temperature, climatic sequence, dry heat, and mixed flowing gas). This interconnect is very stable as a result of the gas-tight metal-to-metal contact from the wiping process during the installation of compliant pin and also from a relatively high normal force applied on the plated through hole (PTH) by the compliant pin. One study[3] even show a compliant pin connection of retention force as low as 2.5 Newton still provides a stable electrical connection under mixed flowing gas conditions for 100 hours. The connection may be still stable for a longer exposure time if the sample is not being pushed out for the mechanical testing after 100 hours exposure of mixed flowing gas.

Two previous studies[2,3] and basic connector mechanics theory have shown stable electrical connections can be achieved using lead-free compliant pin technology; thus, the follow-on investigations[4,5] have focused on evaluating and understanding the mechanical performance and the possible correlations to the coefficient of friction between lead-free PTHs and compliant pins in the connections. One investigation[4] is to evaluate the coefficient of friction (COF) for alternative interfaces between compliant pin and PTH by developing a test apparatus and methodology for the COF. The other investigation[5] was to evaluate the mechanical performance of compliant pin connections using a multi-level full factorial DOE (design of experiments). The DOE was to assess the effects from design/process variables and their interactions on the mechanical performance of the compliant pin connections. The design/process variables in the DOE included lead-free finishes for both PTH and compliant pin, PTH size, repair cycle, and pin stock thickness. Eye-of-the-needle (EON) compliant pin was

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selected in the DOE for testing the connections. The evaluations of mechanical performance included testing insertion and retention forces of the connections. The insertion force is considered as one of important factors to design a complaint pin for selecting the right pin stock thickness and suitable PTH size in the connections without buckling the pin and damaging the PTH during installation. The measurable retention force, an indirect measure of normal force, is considered as an indicator for checking stable electrical connection.

Although a lot of information has been generated from the previous DOE on the effects from different design/process variables and their interactions on the mechanical performance, the scree-plot method from a general statistics package for the analyses only provided limited information on the ranking and statistical significance of the variables and the interactions. In this study, a special package of statistics software Design-Expert® from Stat-Ease® is used to analyze the DOE results from both the current and the previous studies. The software package can provide quantitative information on percentage contributions from the variables and their interactions on the mechanical responses. The quantitative information from the DOE analyses provides another level of insight understanding of the compliant pin connections.

Because pure-tin plating is the preferred coating by the industry for a variety of connector and contact applications[6], both bright and matte pure-tin finishes over nickel were selected in the previous DOE study[5] in addition to the conventional bright tin-lead finish, a baseline for the EON compliant pin connections. Besides the baseline tin-lead, bright tin is again selected in the current DOE study for a further study due to its slightly lower retention force than the bright tin-lead shown in the previous DOE. Also, a gold finish is included in the DOE for its capabilities of lead-free and whisker-free coating.

Even though the pure-tin is the preferred coating by the industry, pure-tin still has some risk of forming tin whiskers under certain environmental and stress conditions. Especially, the growth of tin whisker can be accelerated due to the high compressive stresses experienced by the compliant pins as shown in Figure 1. Thus, tin whisker testing per the iNEMI recommended test requirements is also conducted in the current study to assess the growth for thin whisker of the compliant pin connections.

EXPERIMENTAL PROCEDURES

The following briefly describes the experimental procedures of evaluating mechanical performance and tin whiskers in the EON compliant pin connections.

Mechanical Testing

The same test equipment and procedures in the previous DOE[5] were also used and followed in the current investigation. Single pin tests were used to obtain the insertion and retention force readings per the IEC 60352-5 standard[7]. The travel speed of insertion applications was 25 mm/min, and a speed of 3 mm/min was used for push-out tests. All the push-out tests were conducted on the pins in PTH's after a 24 hours recovery after insertion. A free-floating x-y table was used in testing for a self-alignment of pin with PTH. Also, the same single-layer FR4 test boards of 2.36 mm in thickness with a minimum of 25-50 μm Cu underplate for the PTH's in the previous DOE were used in the current evaluations, and the target PTH conditions of the test boards are summarized in Table 1. The conditions of the EON surface finishes are also listed in the same table. For each combination of the variables in the multi-level full factorial DOE, 5 insertion and 5 push-out tests were conducted in each installation cycle to evaluate the insertion and retention forces of the EON pins in the PTH's.

Tin Whisker Testing

Three environmental conditions are used in this study: room temperature, heat/humidity and thermal cycling conditions. Room temperature conditions were air-conditioned laboratory conditions; although not controlled, the conditions typically were 23 ^{o}C and 30-50% relative humidity for 5000 hours. Heat/humidity conditions were 60 ^{o}C and 93% relative humidity for 5000 and 6000 hours. The heat and humidity values do not directly correspond to the current NEMI requirements[8] since this testing was completed before NEMI reduced the humidity levels they recommended from 93% to 85% RH. The thermal cycling conditions were –40 to 85 ^{o}C, air to air with a 10 minute dwell time and 2500 cycles. The NEMI document requires the application of 5 volts of electrical bias across the lead of the compliant pin connection during environmental conditioning. In the test, each test specimen was a fully populated compliant pin connector containing 60 individual pins. Half of the pins were electrically biased during aging while the other half was stored in PCB without electrical activation.

All specimens were characterized prior to environmental exposure by optical microscopy. No evidence of tin whiskers was seen during initial inspection. It is also noted that there was no preconditioning, such as simulated solder reflow, of any of the specimens used in this study. Most compliant pin connectors are not exposed to the thermal excursions of soldering, thus preconditioning is not appropriate for the specimens. In this study, the inspections were performed by optical and scanning electron microscopy (SEM) with the connectors still loaded into the boards at the certain stages of the testing under environmental conditions. Once the environmental conditions had far exceeded the requirements of the iNEMI test method, the connectors were removed from the PCB and the contacts inspected again for revealing details about the whisker formation on the compliant pins. Although the contacts in the PCB being examined by SEM was problematic due to the electrical charging of the PCB and plastic housing, the inspection was still performed by examining the pins from the bottom side of the PCB and into the PCB hole to the limits practical.

RESULTS AND DISCUSSION

Tables 2 and 3 list the test matrices used in the previous and the current DOE studies, respectively. Also, it is noted that multi-level full factorial DOE is used for both studies. Gold finish is used in the current DOE to replace the matte tin finish for the EON pin in the previous DOE. Only one stock thickness is chosen in the current DOE for the EON pin and therefore four main variables are for the current DOE compared to five variables for the previous DOE. Before discussing the graphical results of using a general statistics package on the effects from design/process variables on the mechanical performance of the lead-free compliant pin connections, the quantitative results from DOE analyses using Design-Expert® are discussed first on the percentage contribution from the variables and their interactions.

DOE Analysis on Mechanical Performance

Tables 4-11 list the DOE analysis results using Design-Expert® on the test data from previous DOE[5] and the current study. The statistics package Design-Expert® calculates the factorial effects in percentage contribution on mechanical performance of compliant pin from the main factors and their interactions in DOE. If the data from both EON compliant pins of thin and thick stocks are incorporated in the analyses, the variable of stock thickness (term E) is outweighing the other variables and interactions in both insertion and retention forces as shown in Tables 4 and 5. The only other factor considered to contributing a significant amount to the insertion force is the PTH size (term B) in Table 4. Otherwise the contributions from the other variables and interactions are small. This is consistent with the results discussed in the previous study[5] using a general statistics package. The above results have confirmed the assumption that the stock thickness of EON is the primarily design factor determining the strength of EON beam and thus the required insertion force for the deformation of EON elastically and plastically during installation. The remaining elastic energy stored in the EON after installation is considered as the primary factor contributing to the applied normal force (and thus retention force) in the connection. Besides the EON stock thickness, the PTH size determines the interference between EON and PTH, and thus the required deformation for the EON during installation. Although the stock thickness being the most contributing factor, the variables and interactions are still considered statistically significant if the values “Prob>F” of these variables and interactions in the tables are less than 0.05 for a 95% confidence level.

Since the stock thickness factor outweighs the other factors in the combined data of both thick and thin pins, we have conducted DOE analysis on the test data only from the same EON of either thick or thin stock. By separating the data for the DOE analyses, more details are obtained on the factorial effects from the DOE analyses. The DOE analysis results are listed in Tables 6-9 for thick and thin stock pins, respectively. Without using the factor of stock thickness in the DOE analyses, PTH size (term B) is coming out as the main contributor for both thick and thin pins on the insertion force and this is followed by installation cycle (term D). The result is as expected, since the PTH size is considered as the primary factor determining the interference between EON pin and PTH and thus the required insertion force. The next contributor of installation cycle is also expected because PTH size is enlarged locally due to the plastic deformation of the PTH from the previous installation. In contrast, the contributions from PTH and EON finishes are relatively small compared to PTH size.

By looking at the percentage contributions on retention force in Tables 7 and 9 for thick and thin stocks, respectively, it indicates that all four main variables and some of their interactions are contributing together to the retention force. Compared to a few factors as the main contributors to the insertion force, the factors affecting retention force are more complex; the retention force may be directly related to the coefficient of friction between EON and PTH and also the normal force applied between EON and PTH. It is generally agreed that the coefficient of friction depends upon the contact interface between EON and PTH of which is determined by EON and PTH finishes after installation. The normal force is dependent upon the PTH size and thus the installation cycle. However, in all possible contributors, the four main variables are still considered as the ranking contributors to the retention force. The only exception is the contribution from the interaction of PTH finish and installation cycle (term AD) in Table 7, and the reason has been discussed in the previous study[5]. This is due to the result that retention force keeps the same level (or slightly increases) as the number of installation cycle increases for the PTH of OSP finish. In contrast, the other five PTH finishes show a typical continuous drop in retention force in the follow-up repair because the PTH size is enlarged from the previous installation. Compared to bright tin-lead finish on EON, the trends of (1) matte tin finish providing higher retention force and (2) bright tin finish providing equivalent or lower retention force have made the EON finish as one of main contributors to the retention force. Also, the results in Table 7 indicate the PTH finish is considered as the most contributing factor for the retention force of thick EON connection. However, the quantitative results from the current DOE analyses are difficult to grasp the whole picture of how the different PTH finishes are responding to the different EON finishes. This will be discussed later in the paper to depict the responses of using different PTH finishes mating with different EON finishes in a graphical way from using the other general statistics package.

Tables 10 and 11 summarize the DOE analysis results on the test data from the current study. As expected, the same results have shown that PTH size is still the primary contributor to the insertion force and this is followed by the installation cycle. The finishes of PTH and EON are contributing relatively small. Similar to the DOE analysis results on the separate test data of either thin or thick stock, four main variables and their interactions are contributing together to the retention force in the test data of current study. Interestingly, the PTH finish is the number one contributor to the retention force and this is similar to the DOE analysis result in Table 7 of using thick stock pin.

The Design-Expert® software so far has provided useful quantitative information on the factorial effects for the DOEs. Based on the information, one can build a statistical model based on the DOE results by selecting and incorporating the statistically significant factors into the model. The effects or trends from the selecting main factors and interactions can then be evaluated based on the model. However, the effects or trends by varying the levels of factors are relatively difficult to be comprehended by the graphics from the current DOE software. For example, for the retention force, the effects or trends are tangling up due to too may interactions and too many levels in the model for the current full factorial multi-level DOE. Therefore, all the trends are based on the statistical model combining with the actual test data. If the trends from the actual test data are the main interests, a general statistics package is better to be used to evaluate the trends instead of using Design-Expert®. In the following discussion, the statistical analyses are only conducted on the factors considered important from the current DOE analyses.

EON Finish on Mechanical Performance

Figure 2 shows the box plots of insertion and retention forces of three different EON finishes during the three installations of the PTH. With all six PTH finishes of full spectrum of seven test PTH sizes, Figure 2(a) shows the EON of gold finish requires a slightly higher insertion force compared to bright tin-lead. The EON of bright tin finish requires equivalent or slightly lower insertion force than the EON of bright tin-lead. The result of equivalent or slightly lower insertion force is similar to the finding on the EONs of bright tin-lead and bright tin finishes in the previous DOE[5]. Although the EON of gold finish requires the highest insertion force, the gold EON provides the lowest retention force as shown in Figure 2(b). For the retention force, equivalent or slightly lower value is observed on using the bright tin EON compared to the bright tin-lead EON (similar to the finding in the previous DOE). Although the data from the current DOE cannot be directly compared with the data from the previous DOE, we can confidently rank the levels of the retention force for the EONs of different finishes as: matte tin > bright tin-lead > bright tin > gold. But, for the insertion force, the ranking is approximately as follows: matte tin > gold > bright tin-lead > bright tin, if counting all three installations for the connections.

By analyzing the test data only in one installation cycle, Figure 3(a) show the gold EON requires the highest insertion force (a slightly higher than tin-lead) and the bright tin EON requires the lowest in the initial installation. The difference of insertion force among the three EON finishes reduces or diminishes in the follow-up 1st repair as shown in Figure 4(a). Similar results have been observed for the 2nd repair, but they are not presented here. The reduction of difference in both 1st and 2nd repairs for the three EON finishes results in the gold EON requiring only a slightly higher insertion force during the three installations for the PTHs as shown in Figure 2(a). However, the rank of the level of retention force remains the same for three EON finishes in individual or combined installation cycles as: bright tin-lead (highest), bright tin (middle), and gold EON (lowest). This is depicted in Figure 3(b) and 4(b) for the initial installation and 1st repair cycle, respectively. The same trend is also found for the 2nd repair.

PTH Size and Finish on Mechanical Performance

Figure 5 shows the insertion and retention forces as a function of PTH size for EON compliant pin connection. The box plots show the median/mean insertion force decreases as the PTH size increases but the median/mean retention force is relative flat regarding to the PTH size. That means the retention force can be considered independent of the PTH size, and this is consistent with the observation in the previous study[5]. A strong function of insertion force regarding to PTH size is consistent with the DOE analysis results showing the PTH size as the most dominant factor for the insertion force. Based on this, when designing the connection, the PTH size should be considered as the most determinant factor for EON compliant pin during the installation of EON pin into PTH whenever a proper alignment is achieved for EON pin and PTH in installation. But, if different stock thickness is to be used for the pin, the effect from the stock thickness may precede the effect from the PTH size.

Figures 6-9 depict the box plots of insertion and retention forces when EONs of different finishes connecting with PTHs of six different finishes in the initial installation from analyzing the data from previous DOE and this study. Here, only the responses of insertion and retention forces in the initial installation are discussed because both EON and PTH are containing their initial surface finish states. Once in the repair stages of EON compliant pin connection, the material transfer[5] from EON to PTH from the previous installation may change the state of PTH finish and then may complicate the response of insertion and retention forces in the connection. It is noted that the variation of median/mean insertion force for different PTH finishes is small for both tin-lead and tin EON finishes compared to gold EON (Figure 6). However, similar median/mean force variations are found for all three EON finishes of tin-lead, bright tin, and matte tin as shown in Figure 8.

By examining the box plots in Figures 6-9, interesting results have been observed. However, before discussing further on the results, we should examine the trend of median/mean insertion force in Figure 6(a) for six PTH finishes using gold EON. Use the trend in Figure 6(a) as an example, the level of the median/mean force, from left to right, can be read as: low → high → low → high → low → low. Similar trends are also observed, more or less, on the two other EONs of bright tin-lead and tin finishes as shown in Figures 6(b) and 6(c), respectively. Compared to the gold EON, the amplitude of the difference between two neighboring low and high is relatively small for the EONs of bright tin-lead and tin. Interestingly, similar trends of insertion force are carried over to the retention force as shown in Figure 7 for the same EON finish. For both bright tin-lead and tin finishes, the difference between low and high in retention force seems to be amplified compared to that of insertion force. The same phenomenon has been also observed on the test results using EONs of bright tin-lead, bright tin, and matte tin finishes in the previous DOE[5] as shown in Figures 8 and 9 during the initial installation. But, most interestingly, the same trend in the initial installation is also observed being carried over, more or less, to the two follow-up repairs. In contrast, the trend is carried over in the current EON tests of bright tin-lead, bright tin, and gold finishes with the exceptions of bright tin-lead and tin EONs engaging with galvanic gold PTH. Both insertion and retention forces are lower when the bright tin-lead and tin EONs are engaging with galvanic gold PTH. But, the trend in insertion force for six different PTH finishes is still carried over to the retention force, more or less. The reason of the similar trends in insertion and retention forces is still unknown. Assuming that the retained normal force between EON pin and PTH has a strong relationship to the insertion force (i.e., normal force $\propto$ insertion force) – presumably due to the elastic energy responsible for the normal force generated during the pin installation. It is unclear if there is a direct correlation between the retention force and the product of normal force (thus, insertion force) and the coefficient of friction between EON pin and PTH.

PTH Distortion

IEC 60352-5 specification[7] requires the transverse sectioning of plated-through hole (PTH) in compliant pin connection technology meets the following conditions: (1) the hole deformation shall be smaller than 70 μm measured by a tangential difference between the drilled hole and the deformed hole, (2) the thickness of the remaining plating thickness must be more than 8 μm, and (3) there is no cracks in the plating of the through hole, in addition to the requirement of no cracks in Cu plating in the longitudinal sectioning of PTH for double side printed board.

In the previous study[5], we have reported that all the PTHs pass the IEC requirements in both longitudinal and transverse sectioning of PTHs after the second repair in compliant pin connections using different combinations of lead-free and tin-lead finishes on both compliant pins and PTHs. At that time, a pass-or-fail criterion was used to check if the distortions of PTHs in the transverse cross-sections at a depth of 0.4 mm below PCB top surface met the IEC requirements. Two concentric circles of a radius in the size of drilled hole and a radius of 70 μm larger than the drilled hole were overlapped on the images of PTHs and then checked if the PTHs passed or failed the requirement of maximum tangential deformation of 70 μm. Also, a straight line of 8 μm in length was used to check if the PTHs exceeded the requirement of minimum remaining plating thickness.

In the current study, we have re-measured the remaining copper plating thickness and the tangential deformation on the transverse cross-sections of most deformed PTHs using image analysis. The measurements of remaining copper thickness and tangential deformation are shown in Figure 10 and summarized in Tables 12 and 13. As expected, smaller PTH size results in larger deformation for the PTH. Also, the results show the most severely deformed PTHs still meet the IEC requirements of (1) the hole deformation shall be smaller than 70 μm measured by a tangential difference between the drilled hole and the deformed hole, (2) the thickness of the remaining plating thickness must be more than 8 μm. Since the measurements were conducted on the most severely deformed PTHs, the PTHs of larger size would also meet the IEC requirements. For the samples of using gold plated EON in the current investigation, we have not completed the evaluations on the PTH distortions yet, and the evaluation results are not reported in this paper.

In contrast to the IEC specification for the transverse sectioning, the results of PTH distortion also show they meet the more stringent requirements of R4-10 in NEBS[9] GR-78-CORE: (1) the average plated-through hole deformation radius shall be no greater than 0.0015 inch (38 μm) when measured from the drilled hole and (2) the absolute maximum deformation radius shall be smaller than 0.002 inch (50 μm). But, other similar requirements in the IEC specification are still called for by the R4-11 of NEBS GR-78-CORE that requires the minimum average copper thickness in the PTH remaining between the pin and the laminate, averaged over a 10-hole microsection sample, shall be no less than 0.0003 inch (8 μm). There shall be no copper cracks or other interplane separation from the PTH barrel or separations between the PCB laminate and the barrel.

Tin Whisker

Tables 14-17 summarize the evaluation results on tin whiskers from EON compliant pin specimens under various environmental conditions. The results show that bright tin-lead over nickel can form whiskers in length of 20-30 μm long on compliant pin. Whisker mitigated matte tin over nickel can form whiskers in length of 20-37 μm long on compliant pin. Whisker mitigated bright tin plating over nickel can form whiskers in length of 20 μm long. All three coatings meet the class 2 requirements in the iNEMI tin whisker acceptance test requirements as shown in Table 18. Of the three environmental conditions used in the whisker test, the heat/humidity condition showed the greatest propensity to accelerate tin whisker growth. The application of electrical bias did not have a consistent effect on whisker growth and does not appear to be statistically significant in accelerating whisker growth when a nickel barrier is employed. The details of the tin whisker testing and the SEM pictures of tin whiskers on the EON compliant pin products can be found in the reference[10].

CONCLUSIONS

A multi-level full factorial DOE has been conducted on the mechanical performance of lead-free EON compliant pin connections using pin finishes of tin-lead, bright tin, and gold. Both DOE data from the current study and a previous investigation have been analyzed by statistics packages on the mechanical performance of the lead-free EON connections. The DOE analysis results have been represented in quantitative and graphical ways to assess the effects from different variables and their interactions on the lead-free EON compliant pin connections. The results are summarized as follows.

- The stock thickness is considered as the single most contributing factor to both insertion and retention forces for the lead-free compliant pin connections if different stock thicknesses are used for the pins.
- The contribution of stock thickness is followed by the PTH size and then the installation cycle for the insertion force of the connections.
- The contributions to the insertion force are relatively small from of the surface finishes of PTH and EON pin, compared to the other three main factors.
- Besides the factor of stock thickness, the four other main factors (PTH surface finish, PTH size, EON pin finish, and installation cycle) and some interactions are contributing together to the retention force.
- The required median/mean insertion force for the different EON finishes are ranked as: gold > bright tin-lead > bright tin.
- The median/mean retention force for the different EON finishes are ranked as: bright tin-lead > bright tin > gold.
- Whisker mitigated matte tin and bright tin can both meet the iNEMI tin whisker requirements.
- Gold coatings on press-fit pins lead to higher insertion forces and lower retention forces, but may be acceptable for certain lead free applications. However, the reduction in tin whisker risk must be compared to the impact on mechanical performance.

Also, by using the whisker mitigated pure-tin coating in either bright or matte appearance on EON pins, the lead-free compliant pin connections meet the IEC requirements of PTH distortion and the iNEMI class 2 requirements for tin whiskers.

ACKNOWLEDGEMENTS

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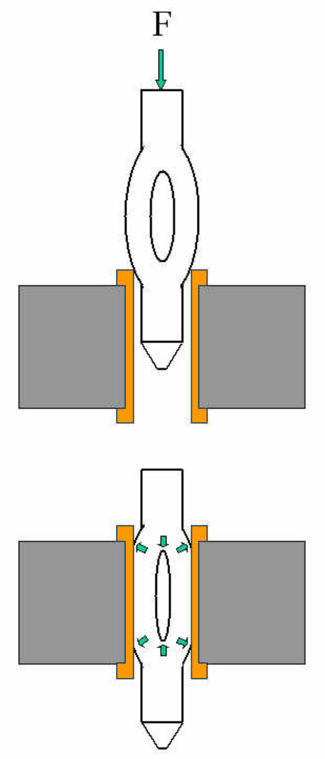
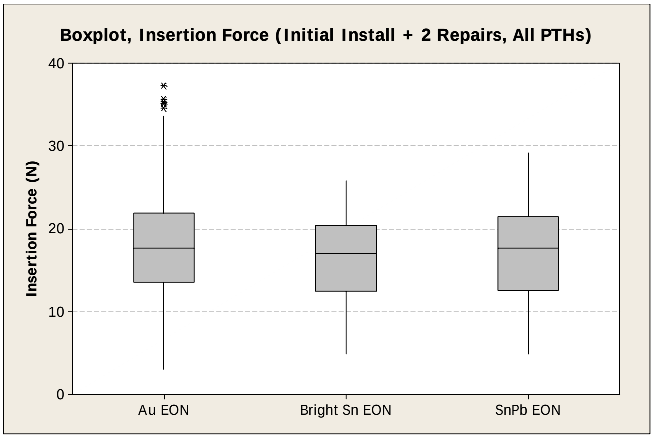
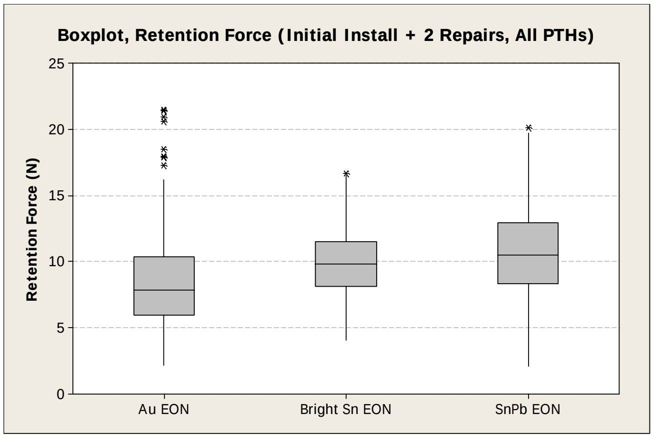


Figure 1. Schematic shows an EON compliant pin being inserted into a PTH (top: EON before insertion; bottom: arrows pointing to the locations of high compressive stresses in EON after insertion).

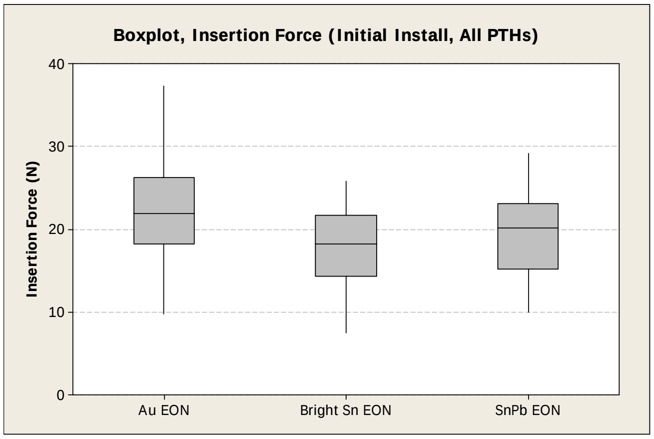


2(a)

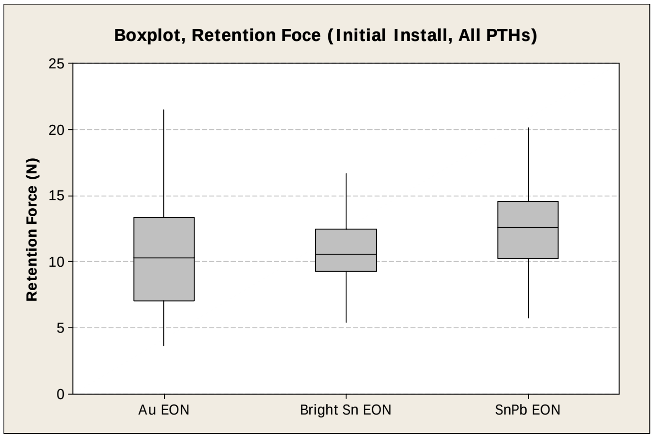


2(b)

Figure 2. Box plots of (a) insertion and (b) retention forces for three different EON compliant pin finishes during initial installation and 2 repairs of all six PTH finishes.

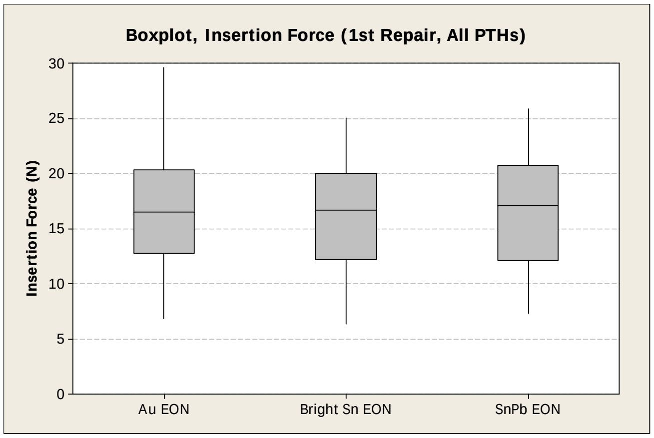


3(a)

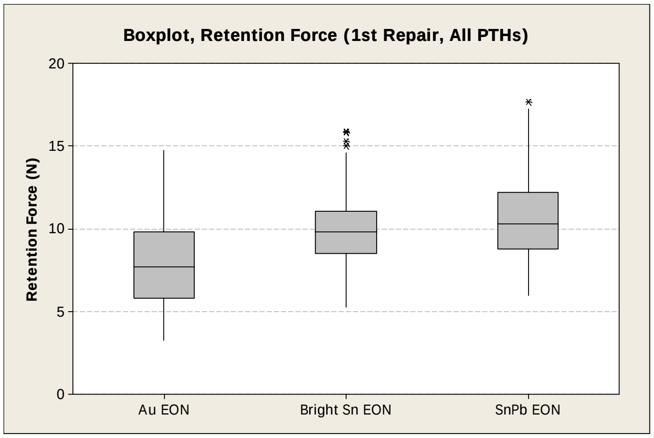


3(b)

Figure 3. Box plots of (a) insertion and (b) retention forces for three different EON compliant pin finishes during initial installation of all six PTH finishes.

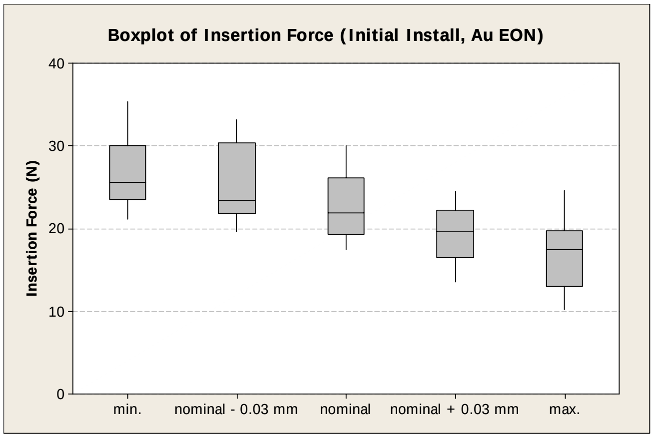


4(a)

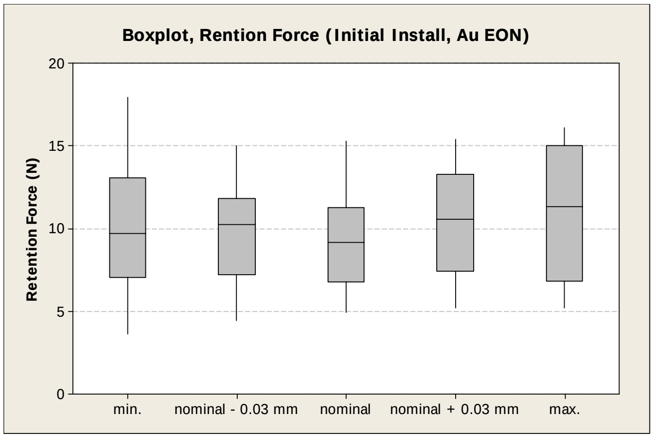


4(b)

Figure 4. Box plots of (a) insertion and (b) retention forces for three different EON compliant pin finishes during 1st repair of all six PTH finishes.

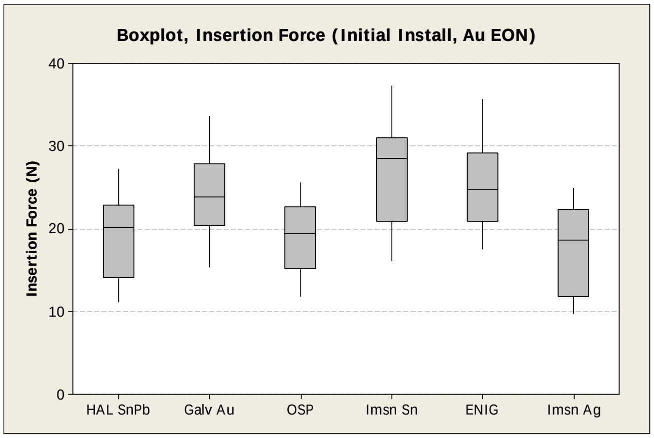


5(a)

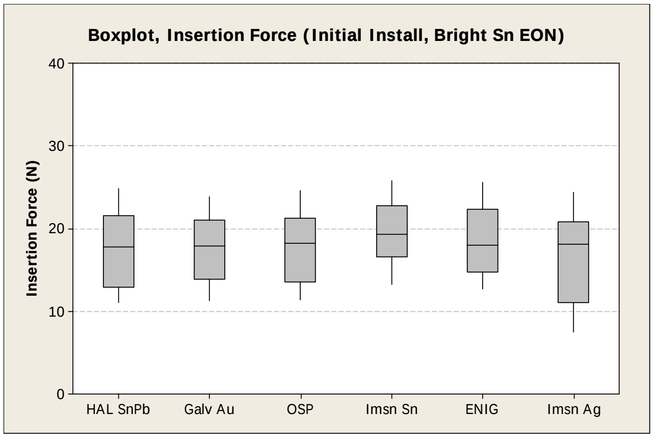


5(b)

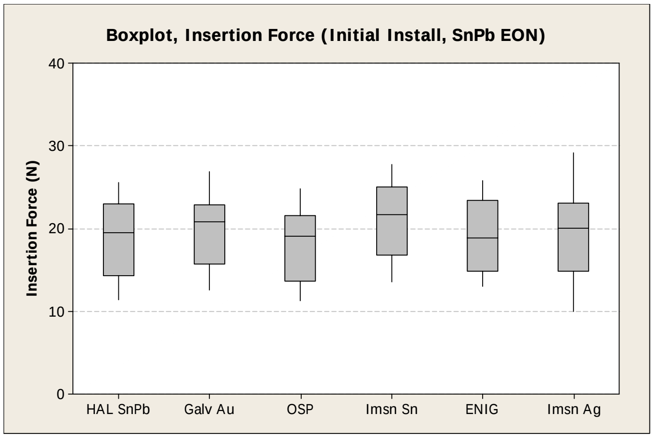
Figure 5. Box plots of (a) insertion and (b) retention forces in terms of PTH size using EON compliant pins of Au finish during initial installation.



6(a)

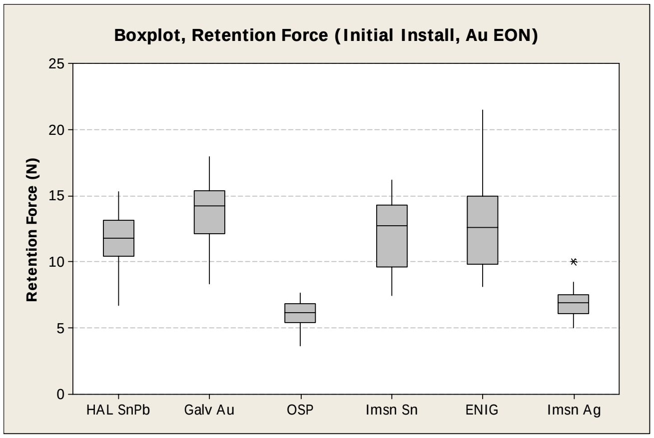


6(b)

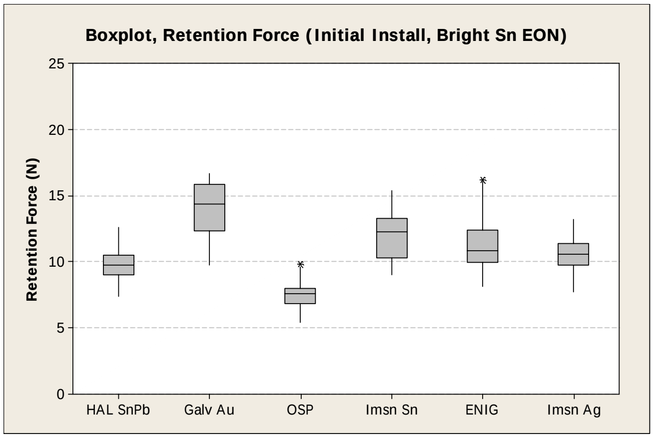


6(c)

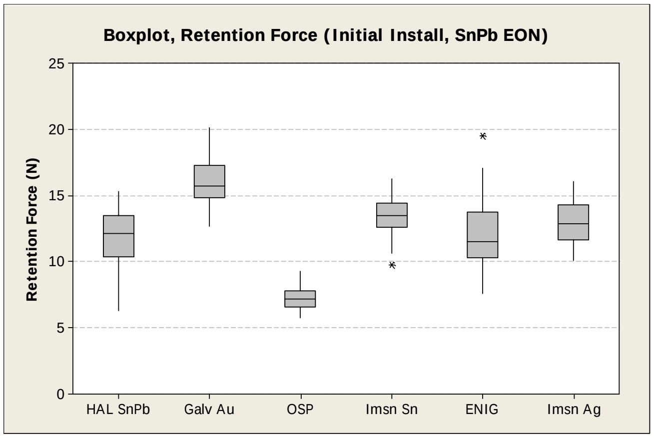
Figure 6. Box plots of insertion force for six different PTH finishes using EON compliant pins with finishes of (a) Au, (b) bright pure-tin, and (c) tin-lead during initial installation.



7(a)

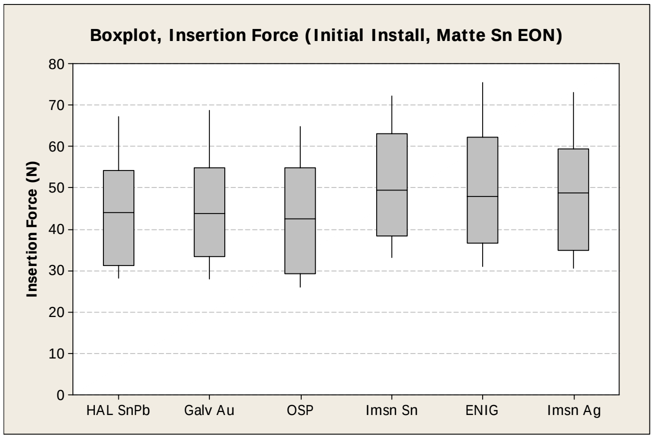


7(b)

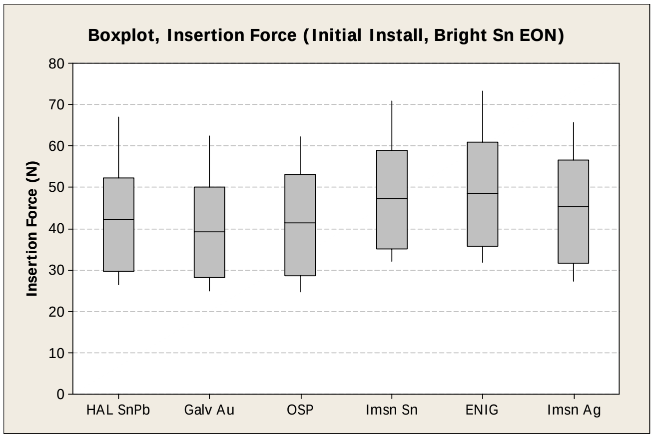


7(c)

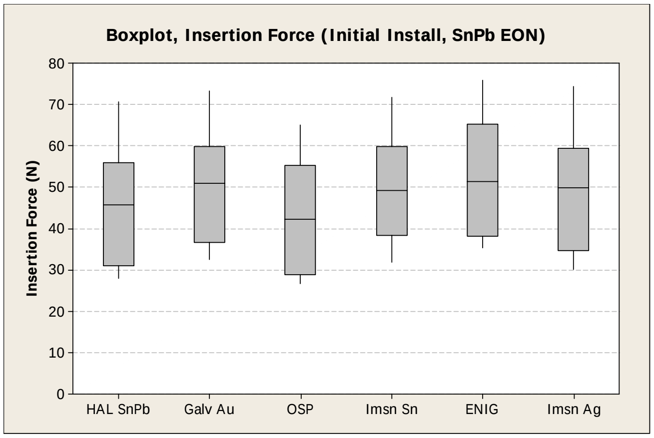
Figure 7. Box plots of retention force for six different PTH finishes using EON compliant pins with finishes of (a) Au, (b) bright pure-tin, and (c) tin-lead during initial installation.



8(a)

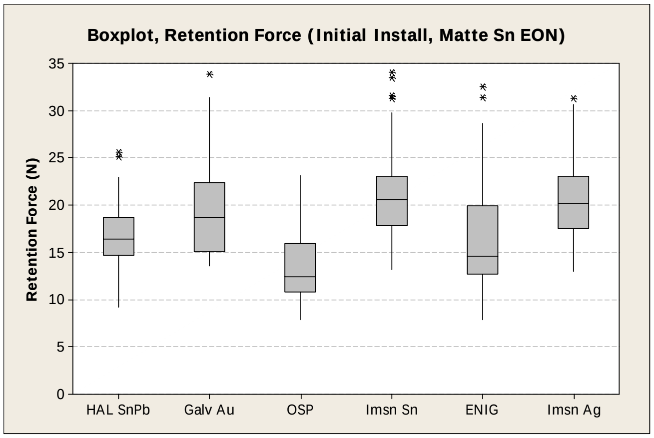


8(b)

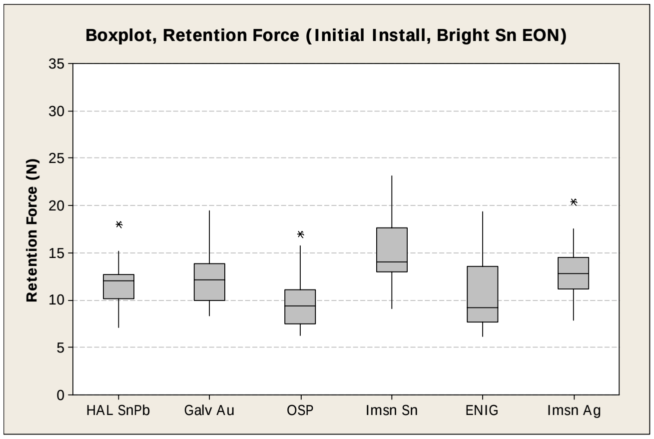


8(c)

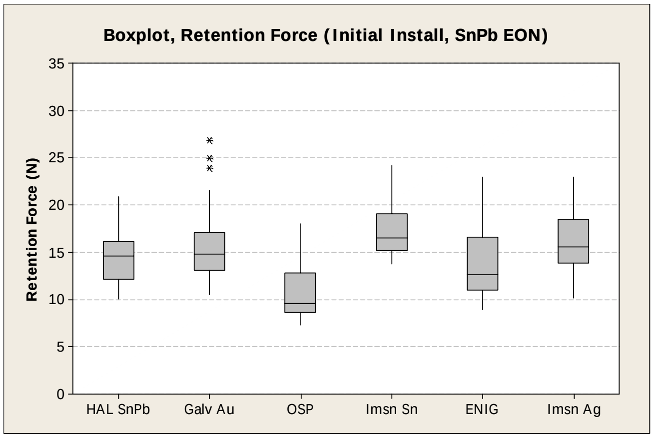
Figure 8. Box plots of insertion force for six different PTH finishes using thin-stock EON compliant pins in previous DOE[3] with finishes of (a) matte tin, (b) bright tin, and (c) tin-lead during initial installation.



9(a)

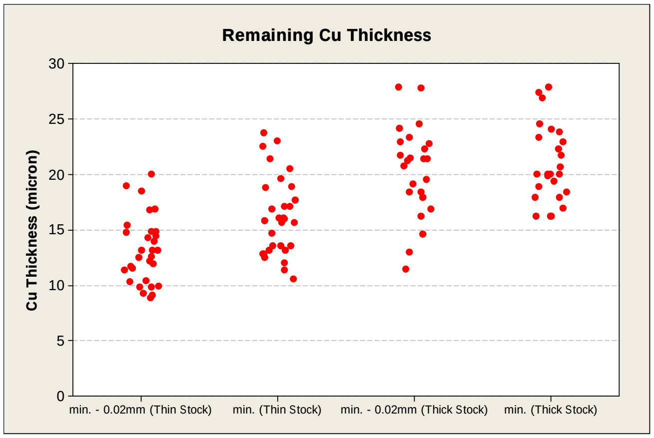


9(b)

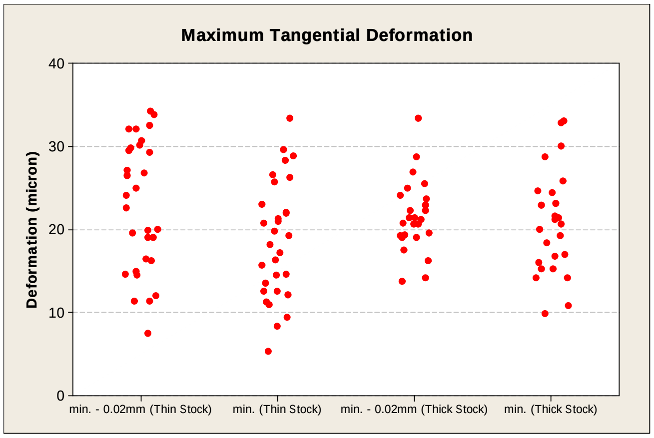


9(c)

Figure 9. Box plots of retention force for six different PTH finishes using thin-stock EON compliant pins in previous DOE[3] with finishes of (a) matte tin, (b) bright tin, and (c) tin-lead during initial installation.



10(a)



10(b)

Figure 10. Hole deformation for compliant pin connections using two different EON stock thicknesses at the most severe conditions (minimum and minimum – 0.02 mm PTH sizes)

Table 1. PCB and EON surface finishes

PCB Coating	Specification
HAL SnPb	35 µm (max.) SnPb
Galvanic Au	4-5 µm Ni + 0.1-0.5 µm Au
Cu + OSP	0.2-0.5 µm OSP
Immersion Sn	0.5 µm (min.) Sn
ENIG	4-5 µm Ni + 0.1-0.5 µm Au
Immersion Ag	0.1-0.15 µm Ag
EON Coating	Specification
Au	0.76 µm (min.) Au over 1.27 µm (min.) Ni
Matte Sn	0.5-2.5 µm matte Sn over 1.27 µm (min.) Ni
Bright Sn	0.5-2.5 µm bright Sn over 1.27 µm (min.) Ni
Bright Sn/Pb	0.5-2.5 µm bright Sn/Pb over 1.27 µm (min.) Ni

Table 2. Test matrix in previous DOE[3]

Level	Variable				
	A	B	C	D	E
	PTH Surface Finish	Target Finished PTH Size	EON Surface Finish	Installation (Repair) Cycle	EON Stock Thickness
1	HAL SnPb	Max. + 0.02 mm	Bright 93/7 SnPb over Ni	Initial Installation	Thin EON
2	Galvanic Au	Max.	Matte Tin over Ni	1st Repair	Thick EON
3	Cu + OSP	Nominal + 0.03 mm	Bright Tin over Ni	2nd Repair	
4	Immersion Sn	Nominal			
5	Immersion Au	Nominal – 0.03 mm			
6	Immersion Ag	Min.			
7		Min. – 0.02 mm			

Table 3. Test matrix in the current DOE

Level	Variable			
	A	B	C	D
	PTH Surface Finish	Target Finished PTH Size	EON Surface Finish	Installation (Repair) Cycle
1	HAL SnPb	Max. + 0.02 mm	Bright 93/7 SnPb over Ni	Initial Installation
2	Galvanic Au	Max.	Au over Ni	1st Repair
3	Cu + OSP	Nominal + 0.03 mm	Bright Tin over Ni	2nd Repair
4	Immersion Sn	Nominal		
5	Immersion Au	Nominal – 0.03 mm		
6	Immersion Ag	Min.		
7		Min. – 0.02 mm		

Table 4. Factorial effects (% contribution) on insertion force from input variables and their interactions for using two different compliant pin stock thicknesses mating with two different targeted PTHs

Term	DOF	SumSqr	MeanSqr	F Value	Prob>F	% Contribution
A	5	13098.1	2619.63	434.673	< 0.0001	1.74302
B	6	210256	35042.6	5814.6	< 0.0001	27.9796
C	2	6525.23	3262.61	541.364	< 0.0001	0.86834
D	2	45987.8	22993.9	3815.36	< 0.0001	6.11979
E	1	379531	379531	62975.4	< 0.0001	50.5058
AB	30	1180.98	39.3661	6.532	< 0.0001	0.157158
AC	10	1560.71	156.071	25.8968	< 0.0001	0.20769
AD	10	4636.33	463.633	76.9304	< 0.0001	0.616976
AE	5	2721.01	544.202	90.2991	< 0.0001	0.362096
BC	12	344.038	28.6698	4.75716	< 0.0001	0.0457825
BD	12	1894.07	157.839	26.1901	< 0.0001	0.252052
BE	6	44280	7380	1224.56	< 0.0001	5.89252
CD	4	1072.91	268.226	44.5066	< 0.0001	0.142776
CE	2	562.892	281.446	46.7002	< 0.0001	0.0749064
DE	2	15077.8	7538.89	1250.92	< 0.0001	2.00646
ABC	60	300.701	5.01169	0.831587	0.8192	0.0400156
ABD	60	551.08	9.18467	1.52401	0.0060	0.0733345
ABE	30	684.261	22.8087	3.78463	< 0.0001	0.0910575
Residuals	3517	21195.8	6.02666			2.8206084

Table 5. Factorial effects (% contribution) on retention force from input variables and their interactions for using two different compliant pin stock thicknesses mating with two different targeted PTHs

Term	DOF	SumSqr	MeanSqr	F Value	Prob>F	% Contribution
A	5	20235.6	4047.11	543.011	< 0.0001	8.96621
B	6	15000.2	2500.03	335.435	< 0.0001	6.64645
C	2	20297.7	10148.8	1361.69	< 0.0001	8.99373
D	2	12314.8	6157.39	826.153	< 0.0001	5.45658
E	1	105599	105599	14168.5	< 0.0001	46.79
AB	30	1897.42	63.2472	8.48604	< 0.0001	0.84073
AC	10	1254.81	125.481	16.836	< 0.0001	0.555995
AD	10	10936.4	1093.64	146.737	< 0.0001	4.84585
AE	5	3753.29	750.658	100.718	< 0.0001	1.66305
BC	12	691.264	57.6053	7.72904	< 0.0001	0.306293
BD	12	367.521	30.6268	4.10927	< 0.0001	0.162846
BE	6	2715.64	452.606	60.7272	< 0.0001	1.20328
CD	4	218.969	54.7423	7.34491	< 0.0001	0.0970236
CE	2	156.835	78.4175	10.5215	< 0.0001	0.0694923
DE	2	1226.52	613.262	82.2828	< 0.0001	0.543463
ABC	60	398.645	6.64409	0.891454	0.7098	0.176637
ABD	60	849.465	14.1578	1.89958	< 0.0001	0.376391
ABE	30	1537.97	51.2655	6.87842	< 0.0001	0.68146
Residuals	3520	26234.9	7.4531			11.62447

Table 6. Factorial effects (% contribution) on insertion force from input variables and their interactions for using thick stock compliant pin mating with its targeted PTHs

Term	DOF	SumSqr	MeanSqr	F Value	Prob>F	% Contribution
A	5	13026	2605.21	609.666	< 0.0001	4.05991
B	6	222219	37036.4	8667.2	< 0.0001	69.2604
C	2	4098.76	2049.38	479.593	< 0.0001	1.27749
D	2	56701.4	28350.7	6634.59	< 0.0001	17.6725
AB	30	1508.48	50.2826	11.7671	< 0.0001	0.470158
AC	10	1904.31	190.431	44.5643	< 0.0001	0.593529
AD	10	6560.94	656.094	153.538	< 0.0001	2.04489
BC	12	289.879	24.1566	5.65309	< 0.0001	0.0903487
BD	12	2893.52	241.127	56.4281	< 0.0001	0.901845
CD	4	1797.38	449.346	105.155	< 0.0001	0.560203
ABC	60	394.319	6.57198	1.53797	0.0057	0.1229
ABD	60	886.538	14.7756	3.45777	< 0.0001	0.276314
ACD	20	1361.07	68.0536	15.9258	< 0.0001	0.424215
BCD	24	246.704	10.2793	2.40555	0.0002	0.076892
ABCD	120	508.783	4.23985	0.992204	0.5080	0.158576
Residuals	1509	6448.21	4.27317			2.00976

Table 7. Factorial effects (% contribution) on retention force from input variables and their interactions for using thick stock compliant pin mating with its targeted PTHs

Term	DOF	SumSqr	MeanSqr	F Value	Prob>F	% Contribution
A	5	19956.9	3991.38	547.537	< 0.0001	24.5084
B	6	6462.39	1077.06	147.751	< 0.0001	7.93625
C	2	11887.7	5943.87	815.379	< 0.0001	14.5989
D	2	10648.1	5324.04	730.351	< 0.0001	13.0766
AB	30	2710.33	90.3442	12.3934	< 0.0001	3.32846
AC	10	1541.38	154.138	21.1446	< 0.0001	1.89292
AD	10	12094.4	1209.44	165.911	< 0.0001	14.8528
BC	12	260.377	21.6981	2.97653	0.0004	0.31976
BD	12	182.377	15.1981	2.08487	0.0153	0.223972
CD	4	254.859	63.7148	8.74038	< 0.0001	0.312984
ABC	60	690.871	11.5145	1.57956	0.0035	0.848437
ABD	60	1251.8	20.8633	2.86203	< 0.0001	1.5373
ACD	20	1274.67	63.7337	8.74298	< 0.0001	1.56539
BCD	24	381.666	15.9027	2.18153	0.0008	0.468711
ABCD	120	808.824	6.7402	0.924619	0.7052	0.993291
Residuals	1512	11022	7.2897			13.5358

Table 8. Factorial effects (% contribution) on insertion force from input variables and their interactions for using thin-stock compliant pin mating with its targeted PTHs

Term	DOF	SumSqr	MeanSqr	F Value	Prob>F	% Contribution
A	5	2750.81	550.162	143.098	< 0.0001	5.44199
B	6	32021	5336.83	1388.11	< 0.0001	63.3479
C	2	2974.71	1487.35	386.862	< 0.0001	5.88493
D	2	4225.56	2112.78	549.535	< 0.0001	8.35952
AB	30	334.929	11.1643	2.90384	< 0.0001	0.662598
AC	10	502.386	50.2386	13.0671	< 0.0001	0.993882
AD	10	379.982	37.9982	9.88335	< 0.0001	0.751727
BC	12	142.033	11.8361	3.07858	0.0003	0.280988
BD	12	125.246	10.4372	2.71472	0.0012	0.247778
CD	4	62.3365	15.5841	4.05344	0.0028	0.123322
ABC	60	248.97	4.1495	1.07929	0.3186	0.492543
ABD	60	330.342	5.5057	1.43204	0.0180	0.653523
ACD	20	114.522	5.72609	1.48936	0.0753	0.226561
BCD	24	105.776	4.40733	1.14635	0.2833	0.209259
ABCD	120	416.126	3.46772	0.901955	0.7641	0.823232
Residuals	1512	5813.14	3.84467			11.50026

Table 9. Factorial effects (% contribution) on retention force from input variables and their interactions for using thin-stock compliant pin mating with its targeted PTHs

Term	DOF	SumSqr	MeanSqr	F Value	Prob>F	% Contribution
A	5	4031.94	806.388	191.737	< 0.0001	10.4295
B	6	11253.4	1875.57	445.959	< 0.0001	29.1094
C	2	8566.76	4283.38	1018.47	< 0.0001	22.1597
D	2	2893.23	1446.61	343.965	< 0.0001	7.48394
AB	30	725.057	24.1686	5.74662	< 0.0001	1.87551
AC	10	332.082	33.2082	7.896	< 0.0001	0.859
AD	10	1546.18	154.618	36.7638	< 0.0001	3.99951
BC	12	800.886	66.7405	15.8691	< 0.0001	2.07166
BD	12	406.735	33.8946	8.0592	< 0.0001	1.05211
CD	4	197.728	49.4319	11.7536	< 0.0001	0.511465
ABC	60	267.421	4.45702	1.05976	0.3551	0.691741
ABD	60	482.813	8.04689	1.91333	< 0.0001	1.2489
ACD	20	122.547	6.12737	1.45692	0.0871	0.316995
BCD	24	204.405	8.51689	2.02508	0.0024	0.528738
ABCD	120	468.913	3.90761	0.929123	0.6928	1.21294
Residuals	1512	6359.01	4.2057			16.44893

Table 10. Factorial effects (% contribution) on insertion force from input variables and their interactions for using thin-stock compliant pin mating with its targeted PTHs

Term	DOF	SumSqr	MeanSqr	F Value	Prob>F	% Contribution
A	5	1974.66	394.932	279.061	< 0.0001	3.44932
B	6	37256.1	6209.35	4387.56	< 0.0001	65.0787
C	2	754.932	377.466	266.72	< 0.0001	1.31871
D	2	7134.73	3567.37	2520.72	< 0.0001	12.4629
AB	30	474.539	15.818	11.1771	< 0.0001	0.828921
AC	10	3704.02	370.402	261.728	< 0.0001	6.47016
AD	10	738.218	73.8218	52.163	< 0.0001	1.28952
BC	12	44.6816	3.72347	2.63102	0.0017	0.0780495
BD	12	82.08	6.84	4.83319	< 0.0001	0.143377
CD	4	1051.96	262.99	185.831	< 0.0001	1.83756
ABC	60	120.382	2.00636	1.41771	0.0209	0.210282
ABD	60	111.867	1.86445	1.31743	0.0546	0.195409
ACD	20	1344.98	67.2489	47.5185	< 0.0001	2.3494
BCD	24	105.913	4.41306	3.11829	< 0.0001	0.185009
ABCD	120	210.319	1.75266	1.23844	0.0464	0.367383
Residuals	1511	2138.39	1.41522			3.735328

Table 11. Factorial effects (% contribution) on retention force from input variables and their interactions for using thin-stock compliant pin mating with its targeted PTHs

Term	DOF	SumSqr	MeanSqr	F Value	Prob>F	% Contribution
A	5	3160.42	632.083	272.422	< 0.0001	18.4195
B	6	414.273	69.0455	29.758	< 0.0001	2.41447
C	2	1545.71	772.856	333.094	< 0.0001	9.00872
D	2	2724.23	1362.11	587.06	< 0.0001	15.8773
AB	30	601.036	20.0345	8.63471	< 0.0001	3.50296
AC	10	1652.01	165.201	71.2004	< 0.0001	9.62826
AD	10	1552.61	155.261	66.9162	< 0.0001	9.04892
BC	12	275.946	22.9955	9.91087	< 0.0001	1.60827
BD	12	270.031	22.5026	9.69843	< 0.0001	1.5738
CD	4	198.324	49.581	21.369	< 0.0001	1.15587
ABC	60	150.269	2.50449	1.07941	0.3188	0.875798
ABD	60	369.814	6.16356	2.65644	< 0.0001	2.15535
ACD	20	737.633	36.8817	15.8957	< 0.0001	4.29907
BCD	24	93.0324	3.87635	1.67067	0.0223	0.542211
ABCD	120	199.101	1.65918	0.715092	0.9903	1.1604
Residuals	1385	3213.52	2.32023			18.72903

Table 12. Average, minimum, and maximum values of minimum remaining Cu thickness measurements in Figure 10(a)

EON Stock Thickness	Thin		Thick	
PTH Size	min. – 0.02 mm	min.	min. – 0.02 mm	min.
Average (μm)	13.18	16.24	20.31	20.98
Minimum (μm)	8.93	10.63	11.48	16.29
Maximum (μm)	20.04	23.78	27.87	27.88

Table 13. Average, minimum, and maximum values of maximum tangential deformation measurements in Figure 10(b)

EON Stock Thickness	Thin		Thick	
PTH Size	min. – 0.02 mm	min.	min. – 0.02 mm	min.
Average (μm)	22.80	18.73	21.59	20.74
Minimum (μm)	7.59	5.36	13.77	9.95
Maximum (μm)	34.30	33.43	33.41	33.13

Table 14. Maximum total length of tin whisker observed after 5,000 hours of room temperature aging with and without applied electrical bias

EON Finish	No Electrical Bias	5 V Electrical Bias
Bright Tin/Lead over Nickel	None Detected	None Detected
Bright Tin over Nickel	15 μm	None Detected
Matte Tin over Nickel	5 μm	5 μm

Table 15. Maximum total length of tin whisker observed after 2,500 cycles of thermal cycling with and without applied electrical bias

EON Finish	No Electrical Bias	5 V Electrical Bias
Bright Tin/Lead over Nickel	None Detected	None Detected
Bright Tin over Nickel	20 μm	None Detected
Matte Tin over Nickel	5 μm	5 μm

Table 16. Maximum total length of tin whisker observed after 5,000 hours of heat/humidity (60^{o}C/93%RH) with and without applied electrical bias

EON Finish	No Electrical Bias	5 V Electrical Bias
Bright Tin/Lead over Nickel	None Detected	None Detected
Bright Tin over Nickel	None Detected	None Detected
Matte Tin over Nickel	37 μm	Nodules Only

Table 17. Maximum total length of tin whisker observed after 5,000 or 6,000 hours of heat/humidity (60^{o}C/93%RH) with and without applied electrical bias after EON compliant pins were removed from PCBs

EON Finish	No Electrical Bias	5 V Electrical Bias
Bright Tin/Lead over Nickel	20 μm	32 μm
Bright Tin over Nickel	18 μm	Nodules Only
Matte Tin over Nickel	16 μm	27 μm

Table 18. iNEMI Tin Whisker Acceptance Test Requirements

Maximum Whisker Length Limits			
Device Considerations (Package type, lead pitch or operating frequency)	Class 1	Class 2	Class 3
Discrete Device (2 pins)	Pure tin and high tin content alloys not acceptable.	40 μm	67 μm
Multi-lead packages			(Minimum gap between leads - .05mm)/3 or 67 μm, whichever is smaller
Operating Frequency > 6GHz (RF) or trise < 59 psec (digital)			50 μm