Effects of Lead-Free Surface Finishes on Press-Fit Connections

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Abstract

For decades, tin-lead has been used as the primary surface finish for compliant pins and plated through holes (PTH) of printed circuit board (PCB) in press-fit connections. Therefore, most test results on press-fit performance are focused on the tin-lead finishes for the connections. Due to the discontinuation of the use of lead in electric and electronic components, the trend of using lead-free manufacturing for PCB's and connectors is being vigorously pursued by the industry. The present study is intended to evaluate press-fit connections using various lead-free finishes on compliant pins and PTH's and then compare to tin-lead finish. The lead-free finishes for the compliant pins are plated with matte and bright pure tin, and the lead-free finishes for the PTH's are electroplated Au, OSP, and immersion tin, Au, and Ag finishes.

In the design of experiments (DOE) of the current study, single pin tests were used to obtain the DOE outputs of insertion and retention forces for eye-of-the-needle (EON) compliant pins in PTH's. For all three EON finishes (two pure tin and one tin-lead), the DOE results show that finished PTH size is the most important factor to determine the insertion force. The insertion force is a strong inverted linear function of finished PTH size (i.e., a larger force is required for a smaller finished PTH size). The impact from pin installation/repair cycle is the second factor behind the finished PTH size. The finishes of EON and PTH are only minor factors for the insertion force. In contrast to the insertion force, the retention force is rather flat regarding the finished PTH size. The DOE results also indicate the EON finish is ranked as the number one factor to affect the retention force. The matte tin EON pin produces higher retention force than the tin-lead finish. The EON of bright tin finish produces a slightly lower retention force than the tin-lead. Within the five lead-free and one tin-lead finishes for the PTH's in the study, the lead-free finishes of OSP, immersion Au and electroplated Au provide retention forces in the lower end, and the immersion tin always provides the highest retention force. However, each of these combinations results in stable electrical performance and a reliable connection.

Introduction

Solderless press-fit connection is one of two most commonly used processes for mounting terminations to PTH's in PCB's for telecommunication equipment and electronic devices. Compliant pins have become dominant press-fit connection due to the disadvantages of using rigid pins, such as, high insertion force, damage to PCB, and loose pins[1]. The press-fit connection helps realize better reliability and economic saving through the absence of problems associated with soldering processes and the ease in manufacturing, assembly, field repair, and changes. It is also noted that most of the problems associated with soldering come from contamination, fluxing, localized heating, cleaning, and solder splashes during the soldering processes.

To maintain stable electrical performances under various environments, it is generally accepted that a minimum retention force is required for a press-fit connection to provide an adequate metal-to-metal contact during the expected life of the connection. The elastic energy, necessary to maintain the normal force (and thus related to the measurable retention force) at the interface during the life of the connection, is stored in one or both of its elements. In the early applications of compliant pin technology in back-plane wire wrap of telecommunications industry, a relatively large retention force of 45 N (10 lb) is required to maintain stable contact interface during the wire wrap process[2]. However, over the years, as the density of connectors continues to increase by reducing the finished PTH size and pin stock thickness, there has been a gradual reduction in the retention force requirements for compliant pins. In the first edition of IEC 352-5 standards (1995), a 20 N retention force was specified for applications without back-plane wire wrap and a 13 N (3 lb) in the EIA standards. As advances continued in PCB density, the computer industry was required to accept compliant pins with lower retention force. In fact, pins have been successfully used in the computer industry with retention forces as low as 7 N (1.5 lb)[2]. To reflect the trend of continuous reduction of retention force, the current IEC standard 60-352-5 (Second Edition, 2001) does not specify the required retention forces. Instead, the connector vendor should define the forces for the applications of press-fit technology.

It is also noted that the gradual trend toward reducing the retention force requirements has been with the use of a conventional interface, tin-lead. Under the directives of banning the use of lead in electric and electronic components, replacements for the conventional tin-lead finishes for PCB's and connectors are actively researched and evaluated. Investigations on the manufacturing issues of different kinds of lead-free finishes have been reported in the literature[3-5]. But, very limited information is available for the press-fit connections of using different combinations of lead-free finishes on PCB's and connectors. Thus, the trends of using lead-free interfaces present a new challenge for the designs and applications of the compliant pins.

Currently, at Tyco Electronics, significant efforts have been devoted to evaluate the performances of compliant pin connection using a variety of alternative lead-free finishes. Tests at Tyco Electronics[6,7] on some selected finished PTH sizes and compliant pin designs indicated that all the contact resistance rises after environmental tests were less than 0.5 mΩ and met the electrical performance requirements in the IEC standards using mechanical and climatic conditioning (vibration, rapid change of temperature, climatic sequence, dry heat, and mixed flowing gas). The very high normal force applied on the PTH by the compliant pin ensures stable electrical performance. Thus, the retention force in compliant pin applications is considered as the most important factor for establishing stable electrical contact and it is the main focus of this study.

In the current study, press-in/insertion forces and subsequently the retention forces were evaluated using single pin tests on eye-of-the-needle (EON) compliant pins. The forces were measured during initial installation, first repair, and second repair cycles for a variety of lead-free and tin-lead finishes on the pins and PTH's. Although the retention force plays the determinant role for the reliability of the press-fit connection, the insertion force is needed to guide the design and application of press-fit connections (such as, material selection for pin and plastic housing). To fully understand the effects of lead-free finishes on EON press-fit connections, multi-level full factorial DOE is used in the study. The input variables for the DOE include PTH finish, finished PTH size, EON finish, EON stock thickness, and installation cycle. In addition to the outputs of maximum insertion and retention forces for the DOE, PTH damage and distortion are also evaluated.

Experimental Procedures

A general-purpose Instron test machine was used in single EON pin tests to obtain the maximum insertion and retention (push-out) forces. The procedures for all the single pin tests follows the IEC 60352-5 standard (second edition, 2001) "Solderless connection–Part 5: Press-in connections–General requirements, test methods and practical guidance". 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 within the time frame of 24 to 25 hours recovery after insertion. Also, in order to have EON pins being inserted into the PTH's in the same orientation for the three installations (i.e. initial installation and two repairs), special designed insertion tools with a free-floating x-y table were constructed for two EON compliant pins of different stock thickness. Special alignment procedures were followed to make sure all the tests having the same orientation between the pins and the PTH's in the PCB. Special designed push-out tools were also used for measuring the retention forces of two types of EON pins, one pin at a time.

The lead-free finishes on the EON pins were plated with whisker-free matte and bright pure tin. Two types of thick and thin EON pins were also included in the study. A variety of commonly available lead-free and tin-lead finishes listed in Table 1 were used for the PTH's. The test boards were manufactured using single-layer standard FR4 board material of 2.36 mm in thickness with a minimum of 25-50 μm Cu underplate for the PTH's. The drilled PTH sizes for different finishes were determined by the PCB vendor to satisfy both the requirements of the PCB finishes in Table 1 and the finished PTH sizes in Table 2. Five input variables listed in Table 2 are used in the full factorial multi-level DOE of this study for evaluating the effects of the variables on the insertion and retention forces (outputs of the DOE) for EON press-fit connections. For each combination of the variables in the 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. A total of 7560 tests were completed in the DOE for the results of EON insertion and retention forces. An optical microscope and image analysis were used to assess the PTH damage and distortions of cross-sectioned PTH's at the depths below PCB surface specified by the IEC standard. Different combinations of EON and PTH finishes were examined for the damage and distortions on some selected finished PTH sizes with pins still in the PTH's.

Table 1 – PCB surface finishes

PCB Plating	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
Immersion Au	4-5 μm Ni + 0.1-0.5 μm Au
Immersion Ag	0.1-0.15 μm Ag

Table 2 – DOE test matrix

Level	Variable 1	Variable 2	Variable 3	Variable 4	Variable 5
	PTH Surface Finish	Finished PTH Size	EON Surface Finish	EON Stock Thickness	Installation Cycle
1	HAL SnPb	Max. + 0.02 mm	SnPb Plating	Thin EON	Initial Installation
2	Galvanic Au	Max.	Whisker-Free Matte Tin Plating	Thick EON	First Repair
3	Cu + OSP	Nominal + 0.03 mm	Whisker-Free Bright Tin Plating		Second Repair
4	Immersion Sn	Nominal			
5	Immersion Au	Nominal - 0.03 mm			
6	Immersion Ag	Min.			
7		Min. - 0.02 mm			

Results and Discussion

Factor Analysis on Insertion Force

The scree test method proposed by Cattell[8,9] was used in the current DOE for factor analysis. The plot from the scree test can graphically capture and determine the importance of input variables (factors) in the test data. The plots in Figures 1 and 2 depict the Cattell scree test results of various factors for the insertion forces of two types of EON pins (thick and thin stock thickness), respectively. For both EON pins, the finished PTH size variable acts as the number one factor to affect the insertion forces. It is followed by the installation cycle variable. The surface finishes of PTH and EON play only minor roles on the EON insertion forces, and no significant effects are coming from the interactions of main variables.

During the press-in process, it is believed that most of the press-in forces are primarily used for the plastic deformation of both the EON pin and PTH. The dynamic friction force to overcome is relatively small compared to the force required for the plastic deformation. For the same design and size of the EON pin, more force is required to press the pin in a smaller PTH than in a larger hole because of the larger interference between EON and PTH. Thus, the finished PTH size is definitely the number one factor to control the insertion force. Although most of the permanent deformation for the enlargement of the PTH occurs during the initial installation of the EON pin in the PTH, it has been observed that the PTH is still continuously enlarged to a certain extent during two follow-up repair cycles. The degree of plastic deformation is still relatively large in the follow-up repairs, and apparently the installation cycle should be considered as the second important factor to affect the insertion force. Since the dynamic friction force is relatively small compared to the force required for the plastic deformation during the press-in process, the EON and PTH finishes only play minor effects on the EON insertion forces. Comparing the scree test values of four effective factors for the two plots of Figures 1 and 2, it indicates that thin stock pin is not as sensitive as the thick stock pin by the effective factors on the insertion force.

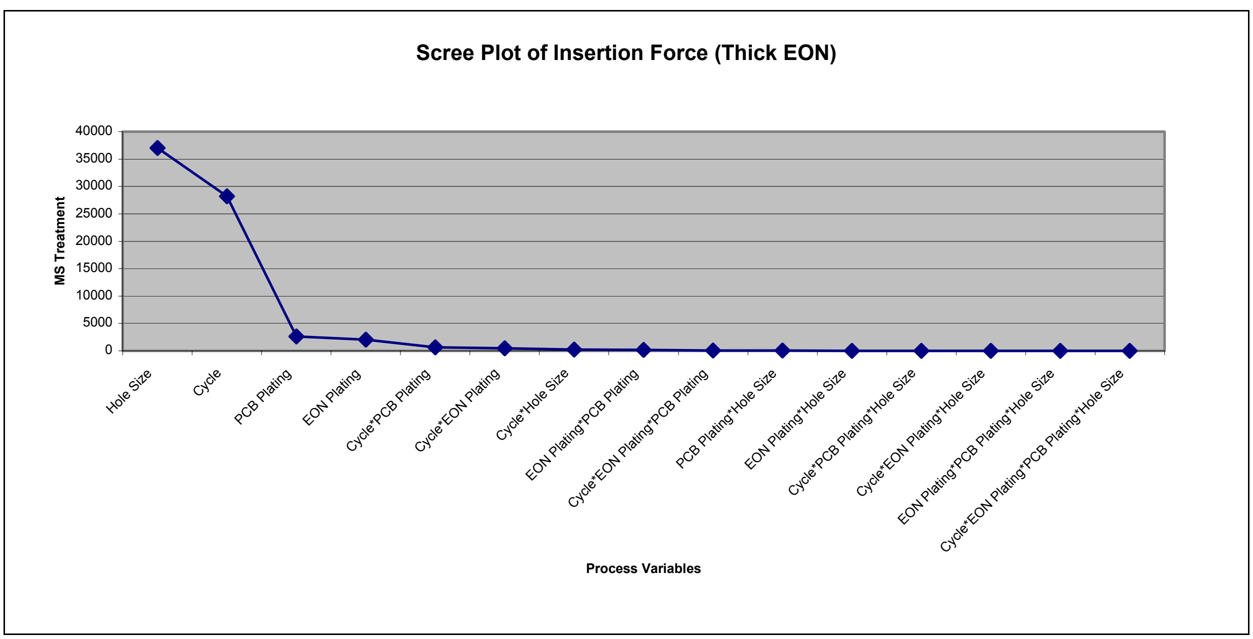

Figure 1 – Screen Plot of Insertion Force for Thick Stock EON Pin

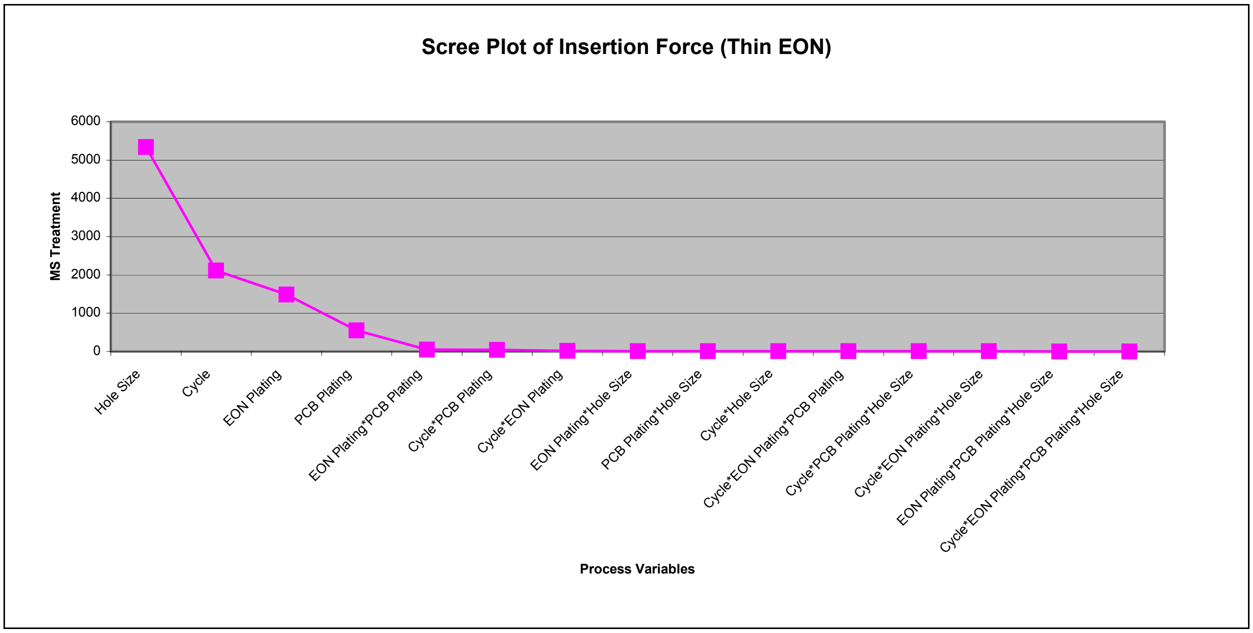

Figure 2 – Screen Plot of Insertion Force for Thin Stock EON Pin

Factor Analysis on Retention Force

For both EON types, the scree plots in Figures 3 and 4 show that four main variables all have certain degrees of effects on the EON retention forces. However, the EON surface finish variable is considered as the dominant factor to control the EON retention force. This is because the retention force is related to the static friction force (or metal-to-metal bonding) between the EON and PTH after press-in. The surface conditions of the EON and PTH after press-in determine the coefficient of friction[2] and then the friction and retention forces. The friction force depends upon the normal force applied on both the EON and PTH, and it is believed that the normal force is highly dependent upon the design of the EON after collapse during press-in and is not so sensitive to the variables of finished PTH size and installation cycle. The possible reason why the EON finish is more effective than the PTH finish to determine the retention force is coming from the material transfer between the soft EON finish and the PTH surface. An example of material transfer is shown in Figure 5. Similar finding was also observed during the work[2] for measuring the coefficient of friction for press-fit connection. However, the actual surface conditions during press-fit are more complex than the simple material transfer. The Ni underplate and copper base metals are also actively involved during press-in and then the retention force.

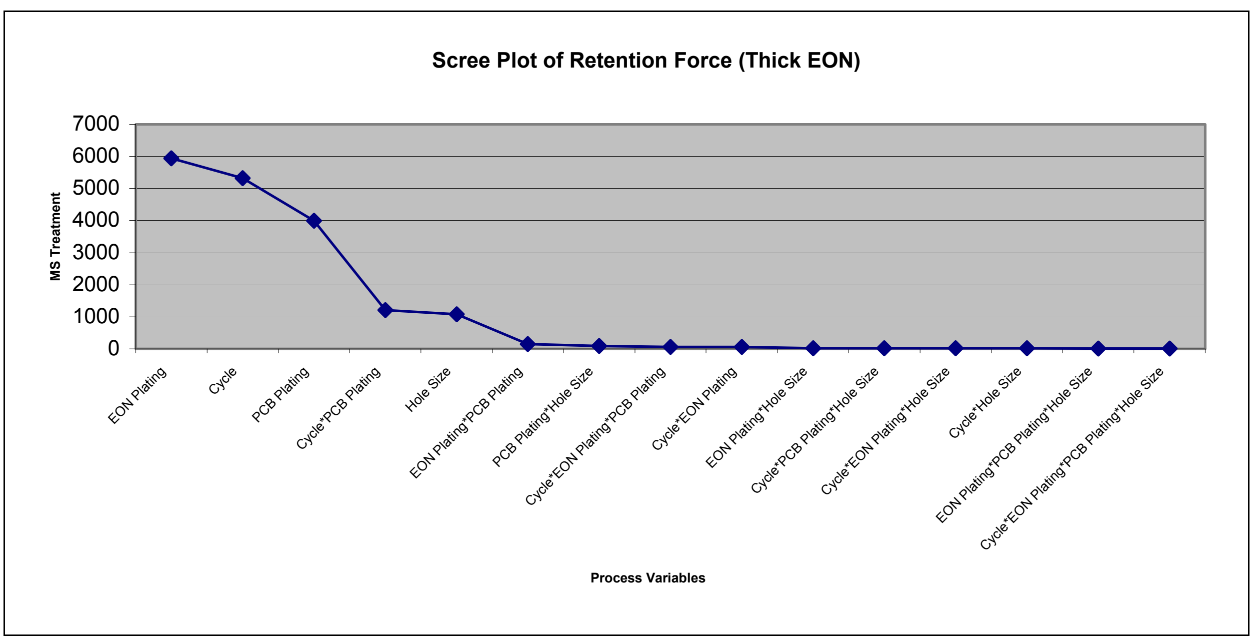

Figure 3 – Screen Plot of Retention Force for Thick Stock EON Pin

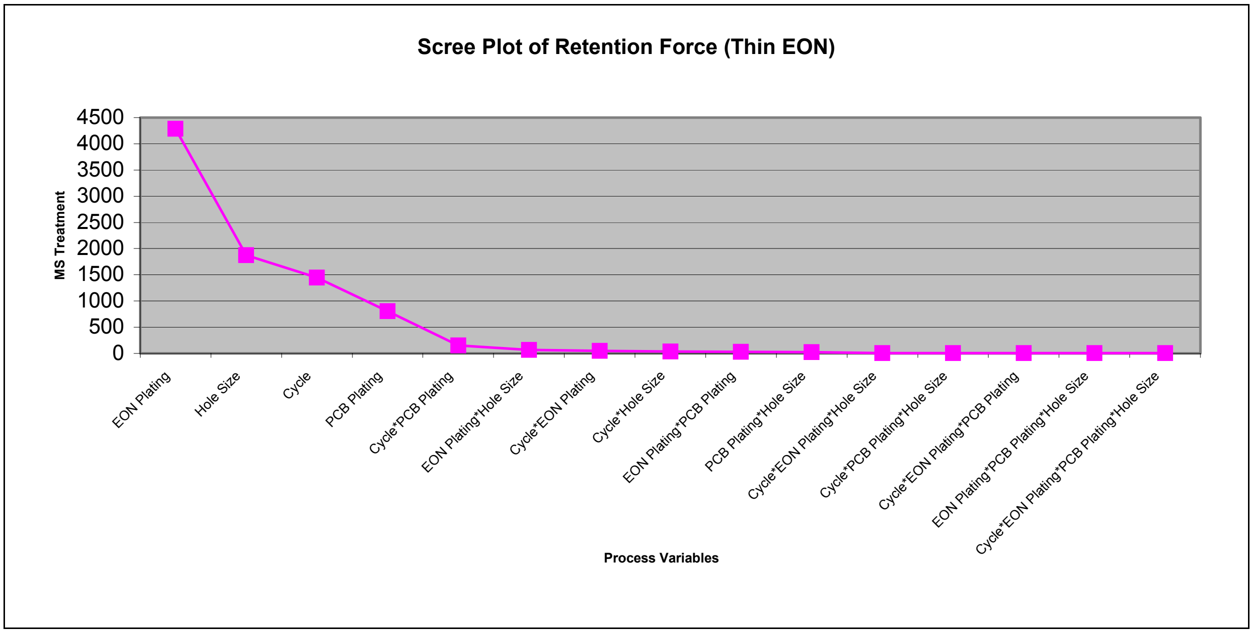

Figure 4 – Screen Plot of Retention Force for Thin Stock EON Pin

Figure 5 – Material Transfer of Soft Tin on EON to PTH (Immersion Au + Ni Underplate)

Although the results of the EON insertion force show that the total deformation of the EON and PTH is highly affected by the variables of finished PTH size and installation cycle during press-in. The elastic portion of the deformation (stored in the EON and/or PTH system, and responsible for the normal force applied on the system) is believed to be highly dependent upon the design of the EON pin. The variables of finished PTH size and installation cycle only play minor roles for storing the elastic energy in the EON and PTH system for the normal force, and thus are considered as the factors behind the EON finish for determining the EON retention force as shown in Figures 3 and 4. In contrast to the results that the thin EON is more insensitive to the effective variables than the thick EON on the insertion force, both EON types are comparably sensitive to the effective variables on the retention force by comparing the test values of two scree plots in Figures 3 and 4.

Effects of Finished PTH Size

The effects of finished PTH size on the insertion and retention forces are shown in Figure 6. The curves show that the insertion force is a strong linear inverted function of finished PTH size for all three installations. However, the initial installation always requires the highest press-in force, and the force is gradually reduced in the follow-up repairs. This is consistent with the observation that the largest deformation always occurs during the initial installation of the EON pin in the PTH. Also, from the spacing between two press-in force curves for two consecutive installations, it indicates that the amount of deformation for the EON and PTH is less in the second repair than in the first repair. Compared to the insertion force curves, the retention force curves are relatively flat and insensitive to the finished PTH size for the current designs of EON pins in the tests. This is consistent with the observations in the work by Cassarly[10].

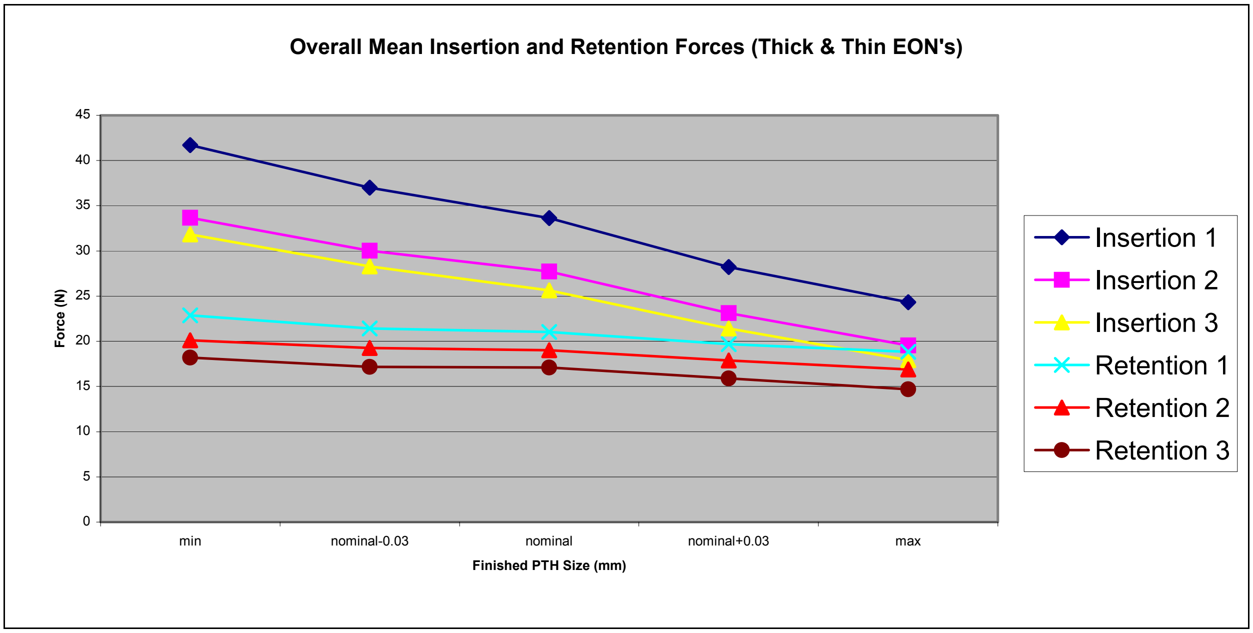

Figure 6 – Overall Mean Insertion and Retention Forces at Different Installation Cycles as a Function of Finished PTH Size

Effects of Installation Cycle

Figure 7 shows the insertion forces of six lead-free and tin-lead PTH finishes during three installations. In general, for all six PTH finishes, the insertion forces decrease as the number of installation cycle increases. Also, as expected, the levels of reductions in press-in forces are more in the first repair than in the second repair. Moreover, within the six PTH finishes, the immersion Sn requires the highest insertion force in all three installations, and the electroplated Au is in the lower end of the force.

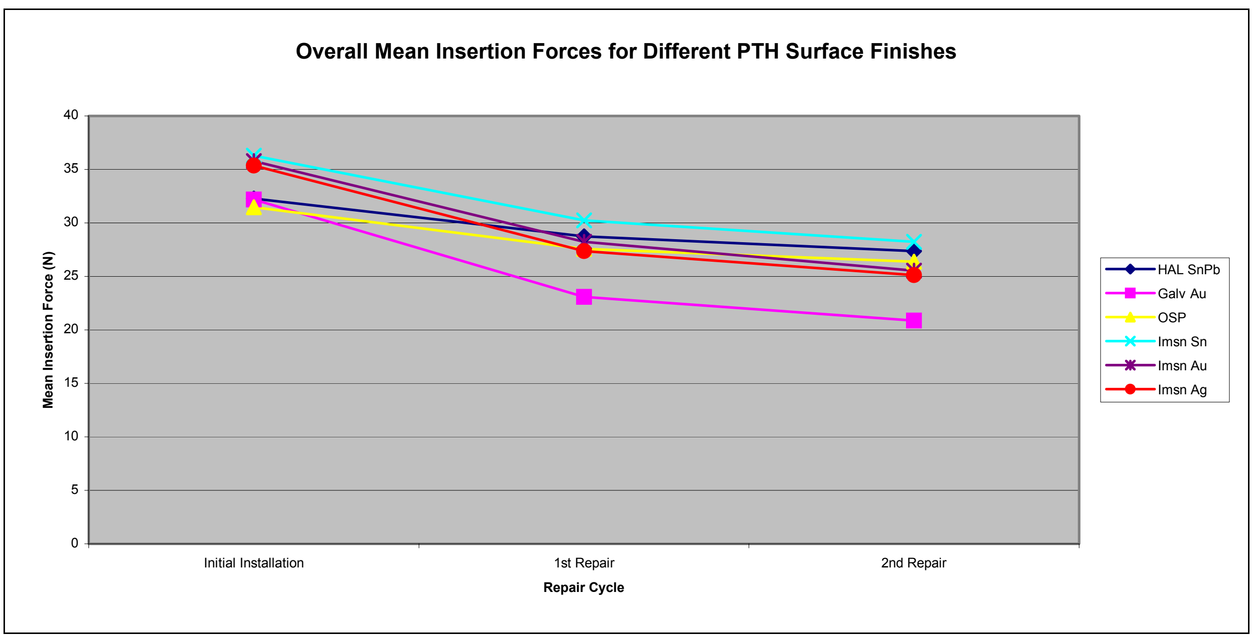

Figure 7 – Overall Mean Insertion Forces for Different PTH Surface Finishes as a Function of Installation Cycle

The retention forces of four PTH surfaces (electroplated Au, immersion Sn, Au, and Ag) shown in Figure 8 depict a continuous reduction in retention force during two follow-up repairs. In contrast, the HAL SnPb finish maintains about the same level of retention force for all three installations, and the retention force is even increased in the follow-up repairs for the OSP finish. Within the six finishes, the immersion Sn always provides the highest retention force in all three installations. Three PTH finishes (OSP, electroplated Au, and immersion Au) are in the lower end of the retention force. Because of the DOE results on the increase and decrease of retention force from the interaction of PTH finish and installation cycle shown in Figure 8, the interaction is considered as an effective factor for the retention force (see the ranking of variables in scree plot of Figure 3).

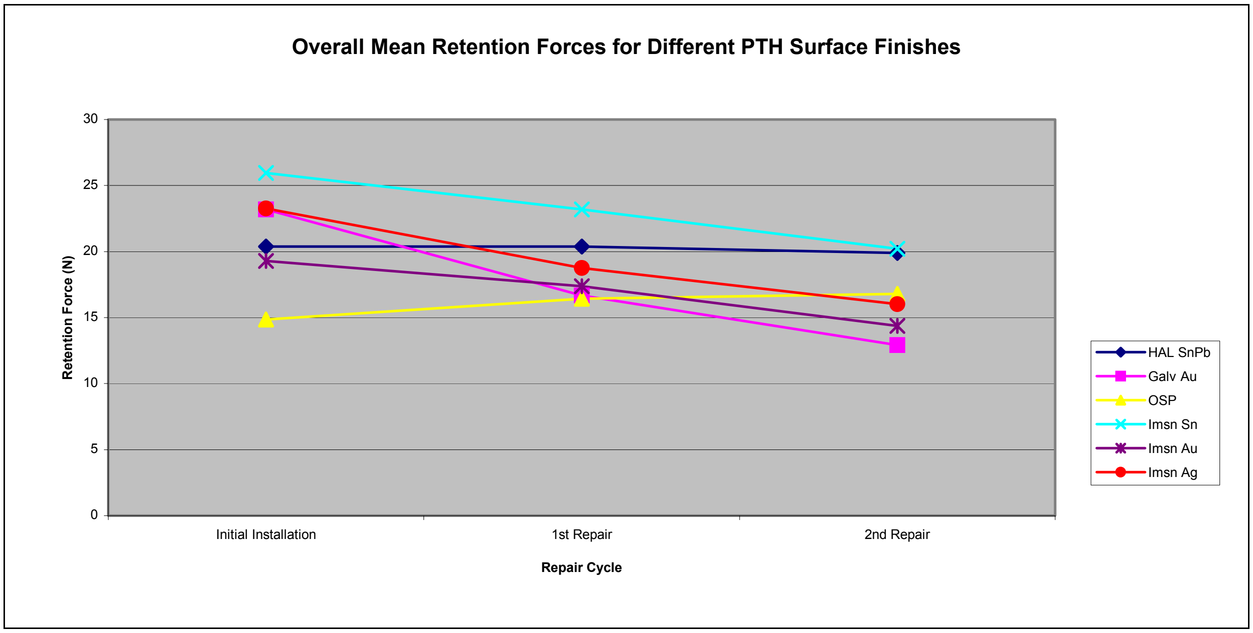

Figure 8 – Overall Mean Retention Forces for Different PTH Surface Finishes as a Function of Installation Cycle

Effects of EON Finish

Figure 9 shows that the matte tin EON requires the highest insertion force and also results in the highest retention force among the three finishes. However, in comparison to the tin-lead EON finish, the gain for the matte tin finish in retention force is more than the increase in insertion force. In contrast, both mean insertion and retention forces for the bright tin EON pins are just slightly lower than those of the tin-lead finish. These statistically significant shifts in force may need to be accounted for in lead-free product design.

Effects of PTH Finish

The overall mean retention forces of three installations are shown in Figure 10 for six PTH finishes. Three PTH finishes (electroplated Au, immersion Au, and OSP) are in the lower end of the retention force, and the other three PTH finishes are in the higher end. To approach the same level of retention force for tin-lead PTH finish, special attention should be put into the applications of EON pins for the PCB’s with the three PTH finishes in the lower end of retention force. With all six finishes, the immersion Sn finish provides the highest retention force for the EON compliant pin connections, and will demonstrate excellent reliability.

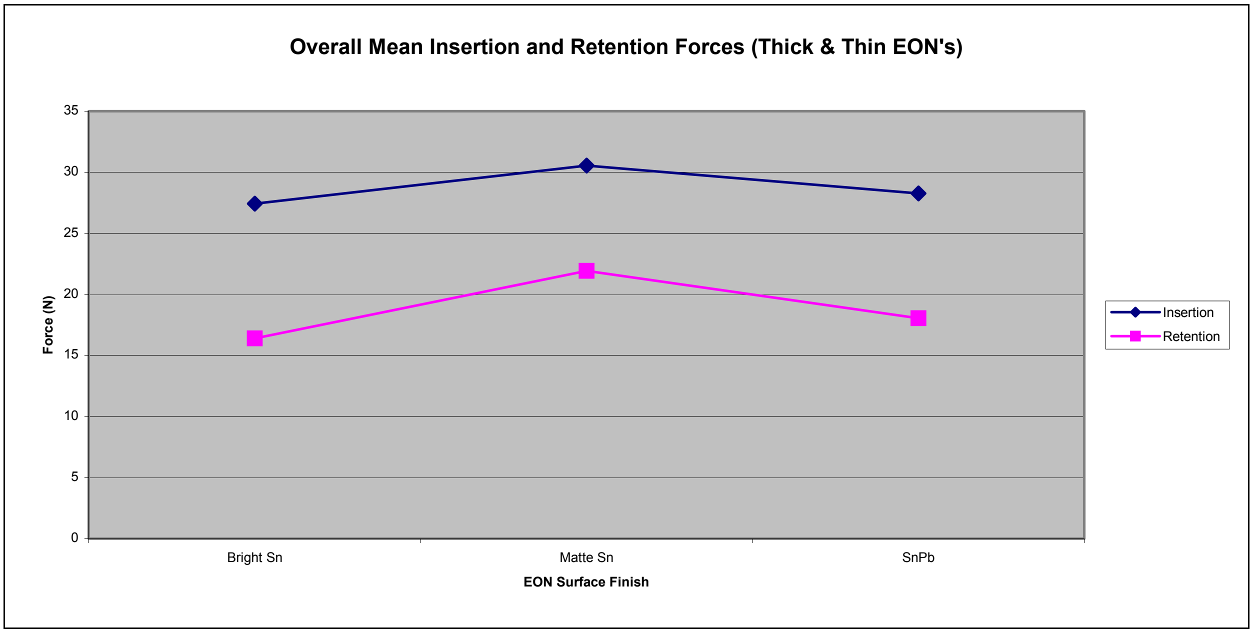

Figure 9 – Overall Mean Insertion and Retention Forces as a Function of EON Surface Finish

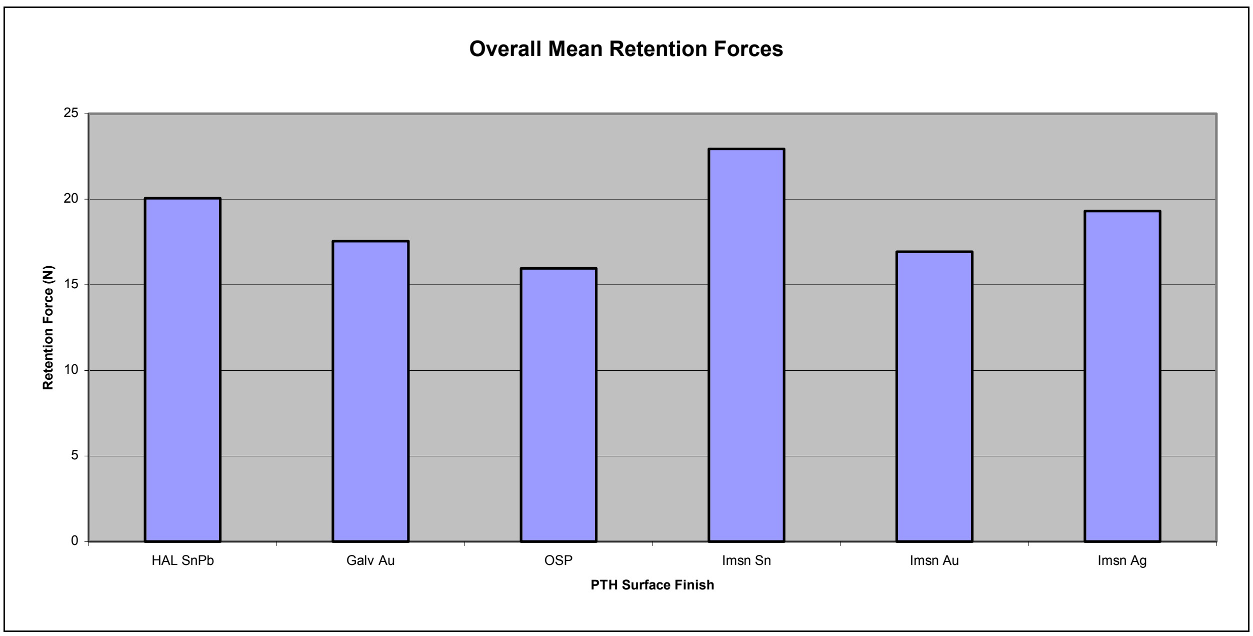

Figure 10 – Overall Mean Retention Forces as a Function of PTH Surface Finish

PTH Damage and Distortion

Following the IEC specifications, the PTH damage and distortions were evaluated on the cross-sections at a depth of 0.4 mm below the PCB top surface with EON pins still in the PTH's after the second repair. Three finished PTH sizes (min.– 0.02, min., and nominal) were examined in the study to evaluate the damage and distortions from different combinations of EON and PTH finishes. The reason of selecting the first two finished PTH sizes is due to the severe deformation on these PTH's. The image analysis results showed that all the examined PTH's met the IEC requirements of minimum remaining copper plating thickness of 8 □m and the maximum tangential deformation of 70 □m for PTH damage and distortion. Figure 13 shows a typical transverse cross-section for a PTH (electroplated Au + Ni finish) with an EON pin in position after the second repair. Moreover, from consecutive cross-sections of PTH's at different depths, it was observed that the Ni underplating in the PTH's for electroplated and immersion Au finishes tended to become thinned and sometimes not existing anymore at certain highly deformed regions of the PTH's. This is primarily a result from the relatively large deformation of the PTH's by the EON pins. However, it was also found that the surfaces of the regions with thinner or no Ni were still protected by the soft tin or tin-lead films due to the materials transfer of soft EON surface finishes to the PTH's.

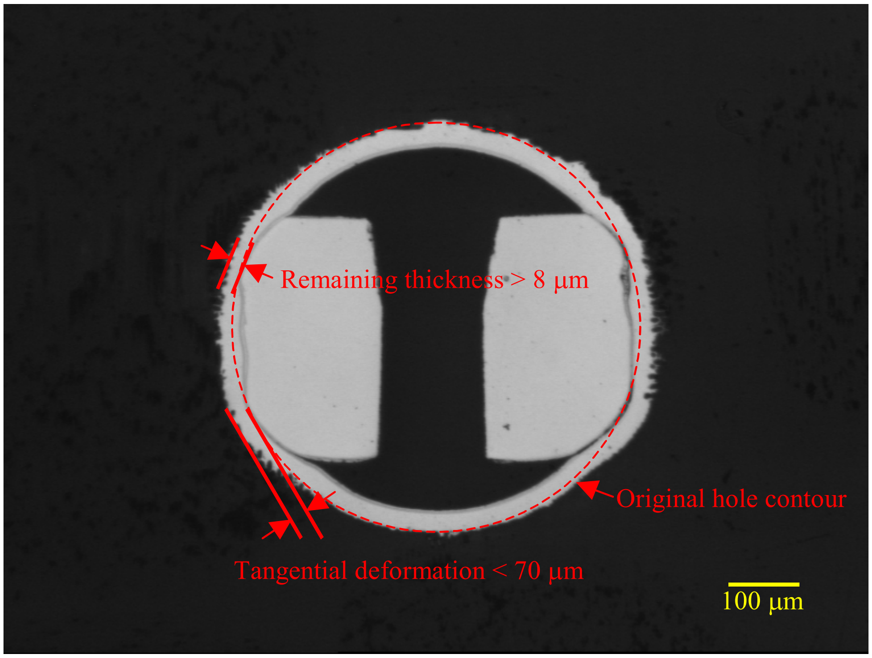

Figure 13 – Typical Cross-Section on Distortion of PTH (Electroplated Au + Ni Finish and Minimum Size) after Insertion of Thick EON (Matte Tin Finish) in Two Repairs

Summary

Various lead-free and tin-lead finishes on EON pins and PTH's have been evaluated in the current DOE study to assess their effects on press-fit connections. The following summarizes the DOE results and observations from cross-sections of PTH's after two EON pin repairs.

All the main input variables in the DOE are considered to affect the EON insertion force. But, for all three EON finishes (two pure tin finishes and tin-lead), the finished PTH size is ranked as the number one variable to affect the EON insertion force, and the insertion force is a strong inverted linear function of finished PTH size. In contrast, the EON retention force is relatively flat regarding the finished PTH size.

The installation cycle is ranked as the second important factor to affect the insertion force, and the EON insertion force is reduced as the number of repairs increases. The same trend of reduction is also observed for the EON retention force.
For the insertion force, the EON's of thin stock thickness are more insensitive to the input variables in the DOE than the EON's of thick stock thickness.

All the main input variables in the DOE affect the EON retention force. But, the EON finish acts as the dominant factor to control the EON retention force. This may be due to the surface condition change of PTH by the material transfer of soft EON finishes to the relative harder PTH surface.

Compared to the tin-lead EON, the matte tin EON requires higher insertion forces but also provides even higher retention forces. In contrast, the bright tin EON requires lower insertion forces and provides slightly lower retention force than the tin-lead EON.

The EON retention forces are in the lower end for the lead-free PTH finishes of OSP, immersion Au, and electroplated Au, but the immersion Sn finish always provides the highest retention force in the test group.

At a depth of 0.4 mm below the PCB top surface, the cross-sections on the PTH's after the second repair showed all the PTH's met the IEC requirements of minimum remaining copper plating thickness of 8 µm and the maximum tangential deformation of 70 m for PTH distortion.

The actual drilled PTH sizes and Cu plating thickness of various lead-free finishes are not reported in the current study. Their effects on the insertion/retention forces of press-fit connections will be evaluated in the future studies.

Acknowledgement
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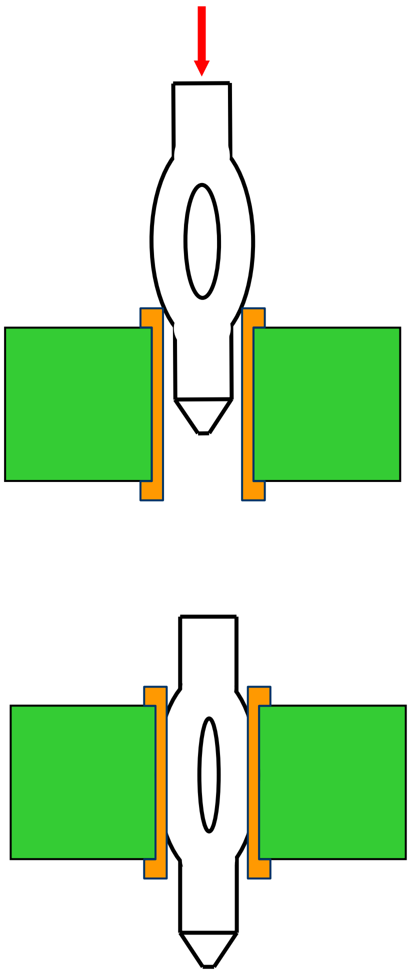
Objectives

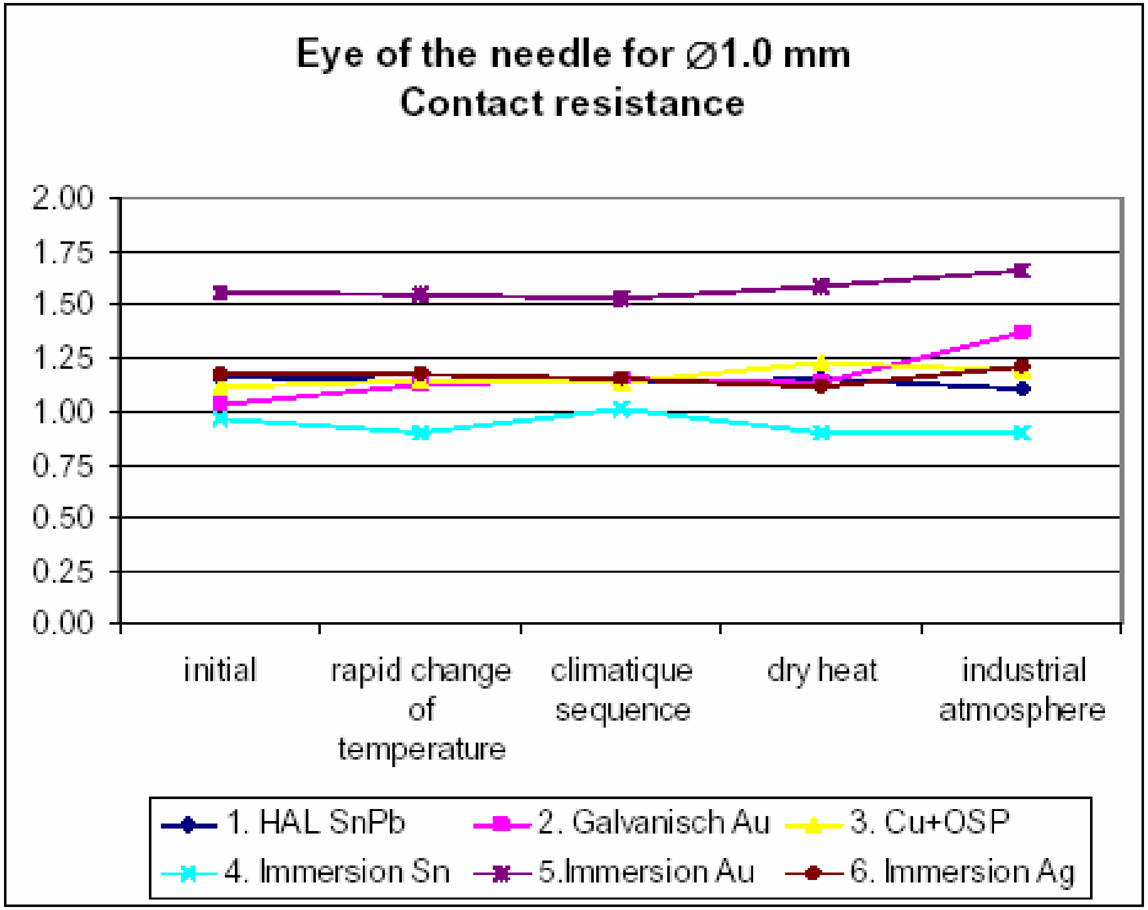
- Evaluate press-fit connections from using various lead-free surface finishes on EON compliant pins and PCB PTH’s
- Compare to conventional tin-lead finish
- Recommend on lead-free press-fit applications

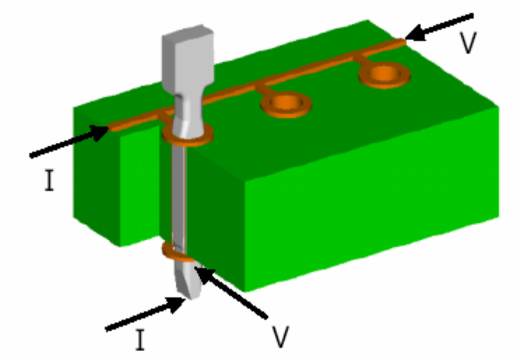
Advantages of Press-Fit Connections

- Easy in manufacturing, assembly, field repairs and changes
- Surface-mount compatible
- Environmentally friendly (no heat and no cleaning)
- Highly reliable (even in high vibration & thermal cycling environment)
- Eliminating the problems associated with soldering
  - Solderability issues
  - Contamination
  - Fluxing
  - Localized heating
  - Cleaning
  - Solder splashes



Previous Results on Contact Resistance



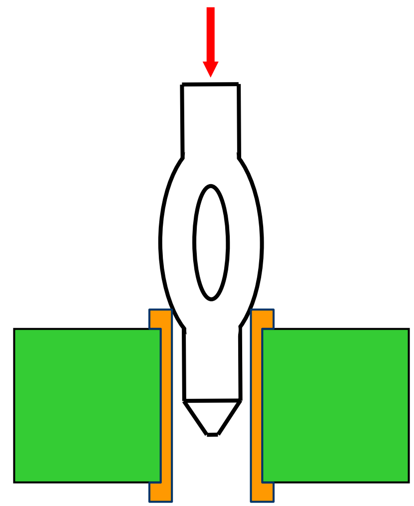


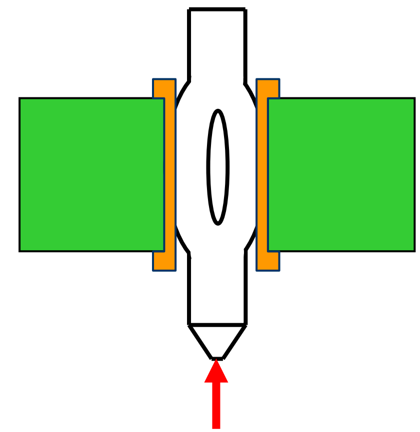
- Erick Verhelst, Chapter 07.05, 21th ICEC Zurich, (September, 2002)
- Bright tin EON

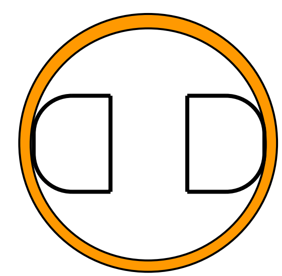
- Contact resistance variations < 5 mΩ (IEC spec.)
- High normal force ($\propto$ retention force) $\Rightarrow$ reliability

Evaluation Approaches

- Multi-level full factorial DOE
- Input variables
  - Board finish
  - EON pin finish
  - Repair cycles
  - Hole size
  - Pin stock thickness
- Outputs
  - Insertion force ($\Rightarrow$ PTH damage, housing design & pin buckling)
  - Retention force ($\propto$ normal force $\Rightarrow$ contact resistance)
- Single pin testing
  - As per IEC 60352-5







Multi-Level Full Factorial DOE

Level	Variable 1	Variable 2	Variable 3	Variable 4	Variable 5
	PTH Finish	PTH Size (mm)	EON Finish	EON Stock Thickness	Repair Cycle
1	HAL SnPb	Max. + 0.02	SnPb	Thin EON	Initial Installation
2	Galvanic Au	Max.	Matte Tin*	Thick EON	1st Repair
3	Cu + OSP	Nom. + 0.03	Bright Tin*		2nd Repair
4	Immersion Sn	Nominal			
5	Immersion Au	Nom. - 0.03			
6	Immersion Ag	Min.			
7		Min. - 0.02			

* Whisker free plating with Ni underplate

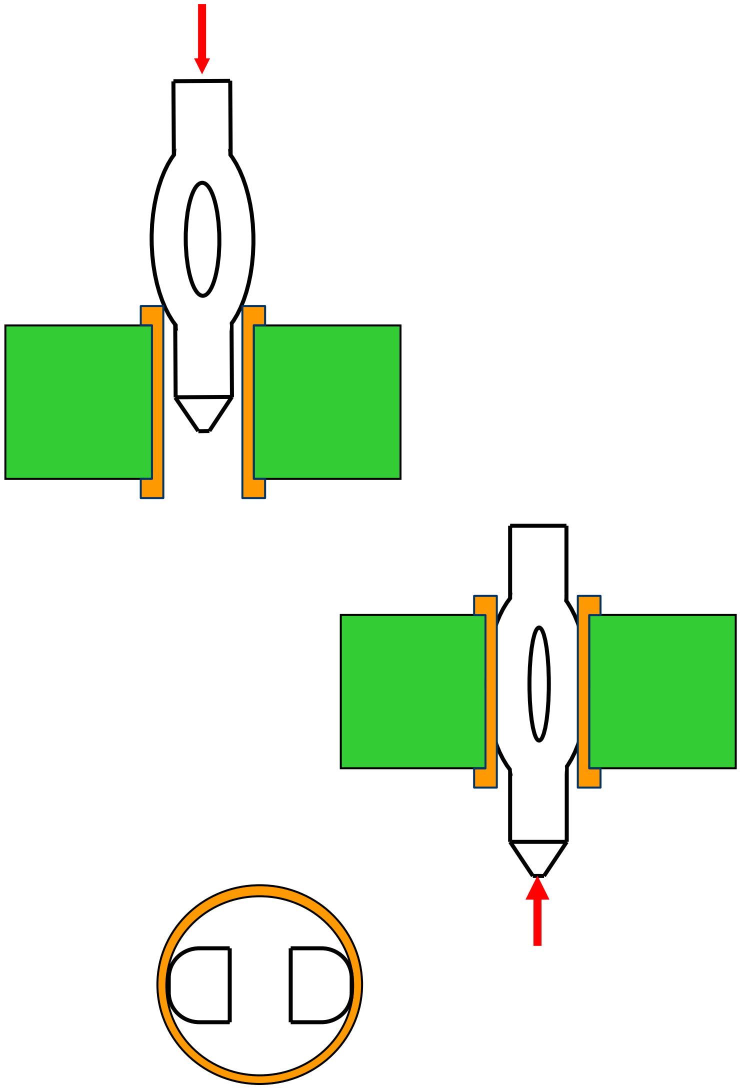
PCB Surface Finishes

PTH Finish	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
Immersion Au	4-5 μm Ni + 0.1-0.5 μm Au
Immersion Ag	0.1-0.15 μm (min.) Ag

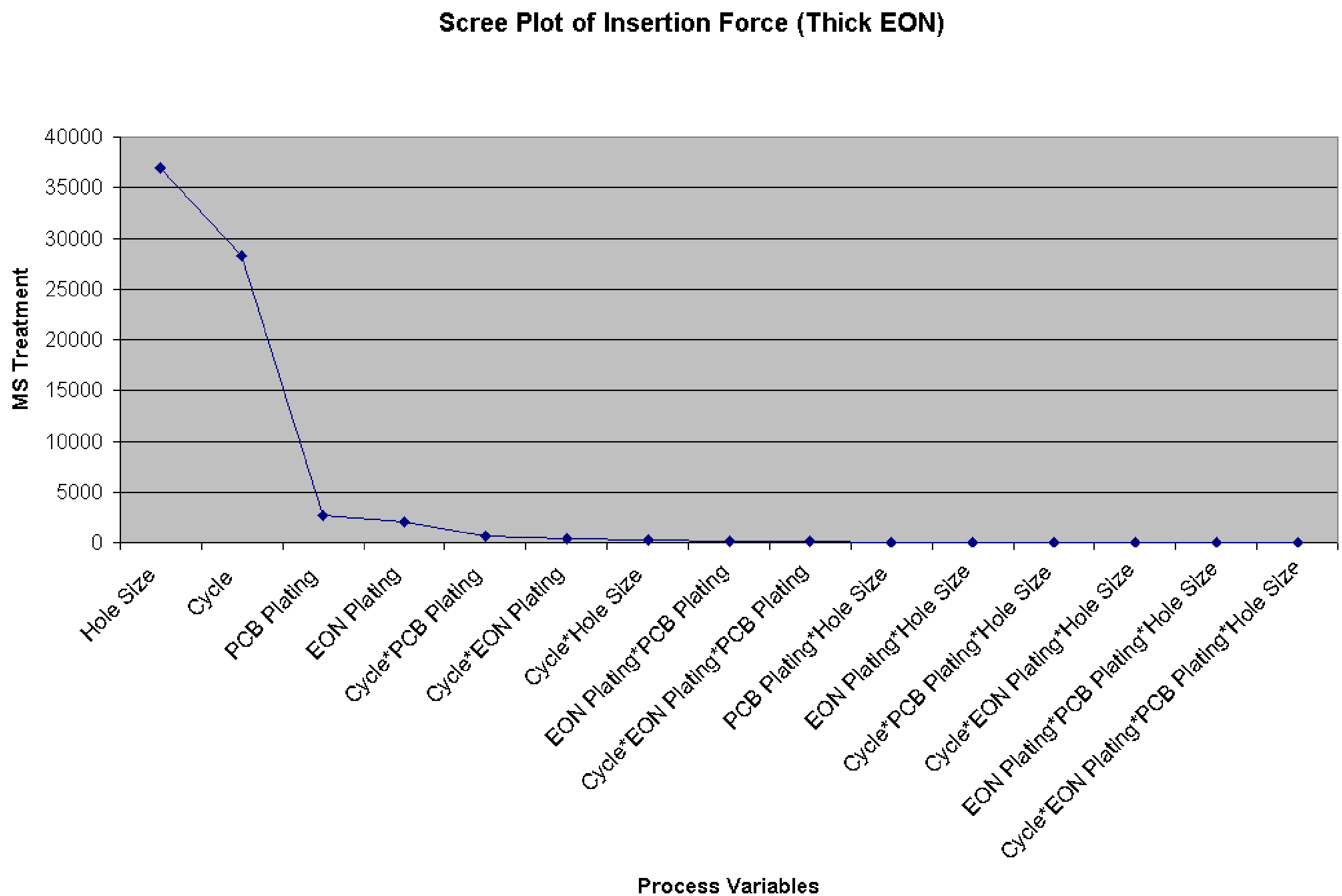
- Base material: FR4
- Board thickness: 2.36 mm
- Underplate: 25-50 μm Cu

Test Procedures

- As per IEC 60352-5
- Insertion force
  - Press-in test
  - 25 mm/min travel speed
- Retention force
  - After 24 hours recovery
  - Push-out test
  - 3 mm/min travel speed
- Special designed test fixtures and alignment procedures
- Visual examination
- Microsectioning (PTH distortion)

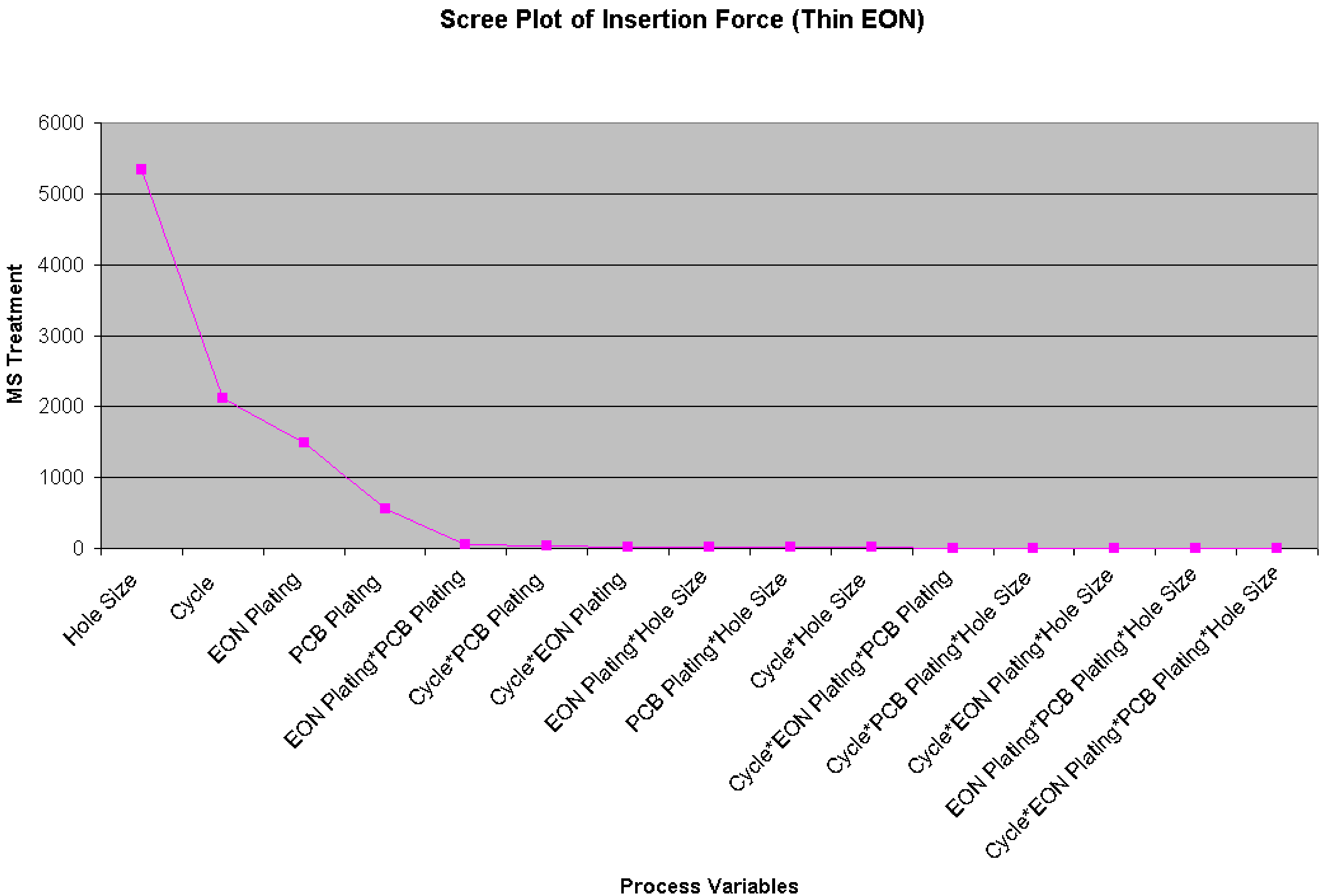


Factor Analysis-Insertion Force (Thick EON)



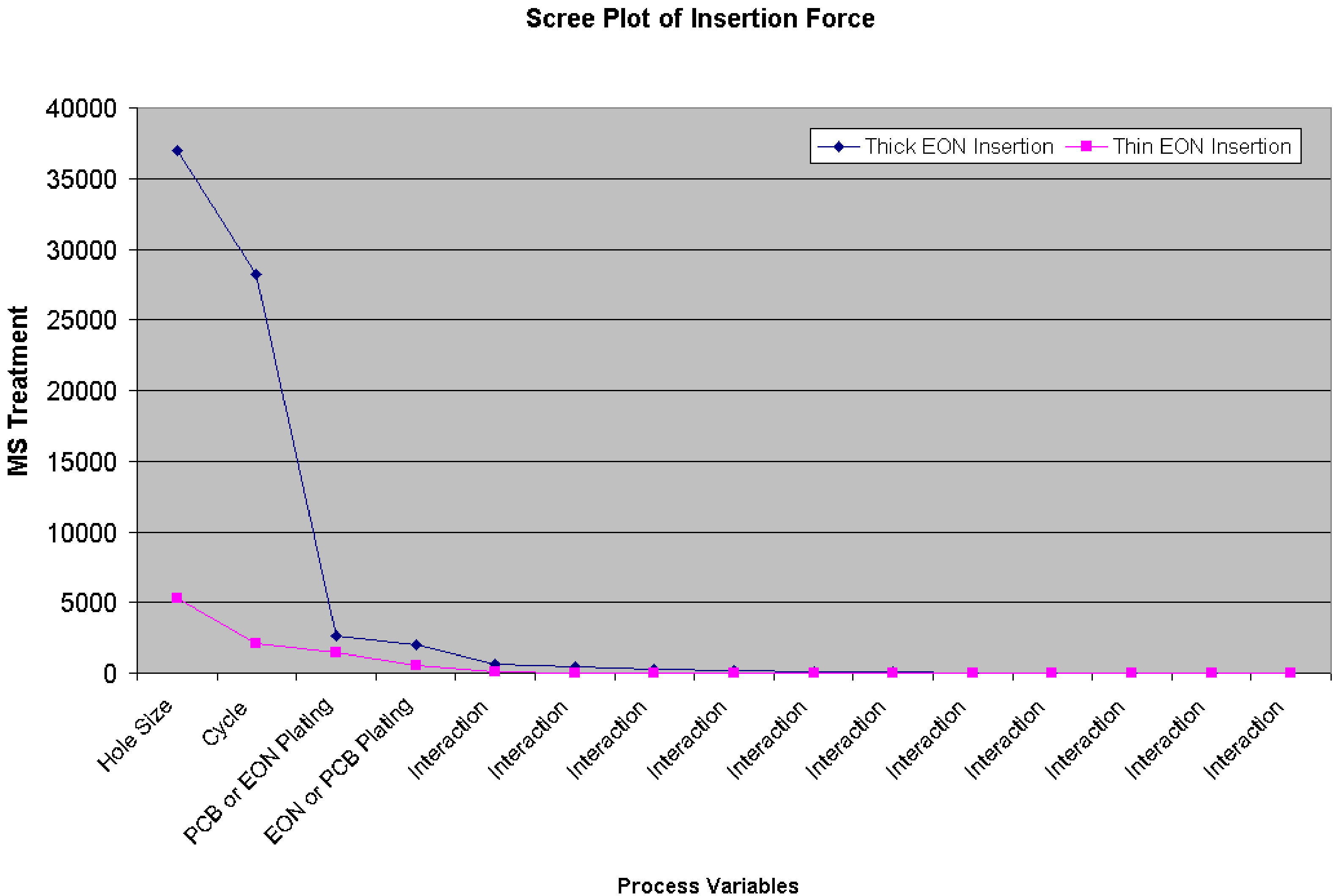
- 4 effective factors on retention force for thick stock EON
  - Hole Size > Repair Cycle > PCB Plating > Pin Plating

Factor Analysis-Insertion Force (Thin EON)



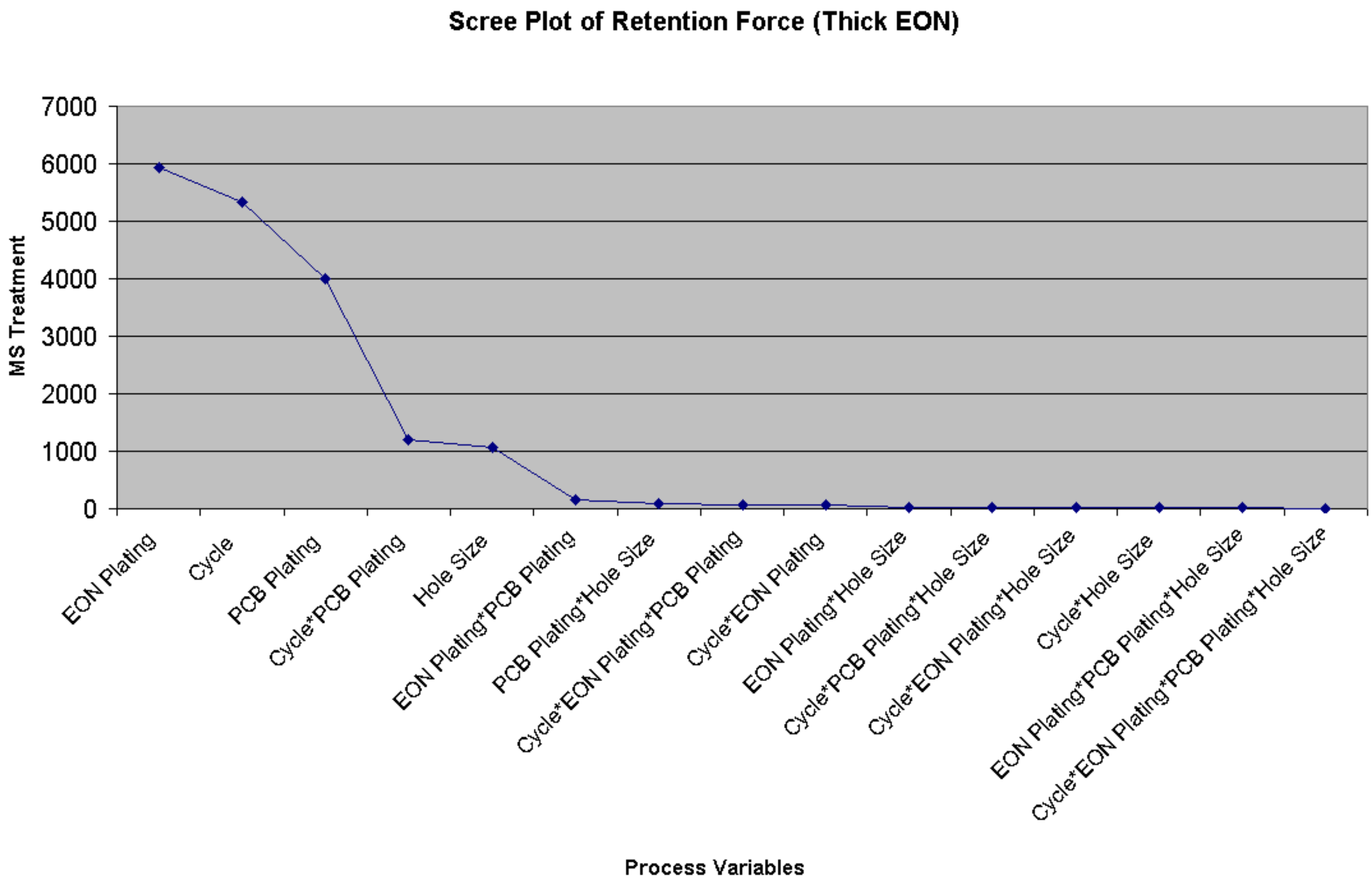
- 4 effective factors on retention force for thin stock EON
  - Hole Size > Repair Cycle > Pin Plating > PCB Plating

Factor Analysis-Insertion Force



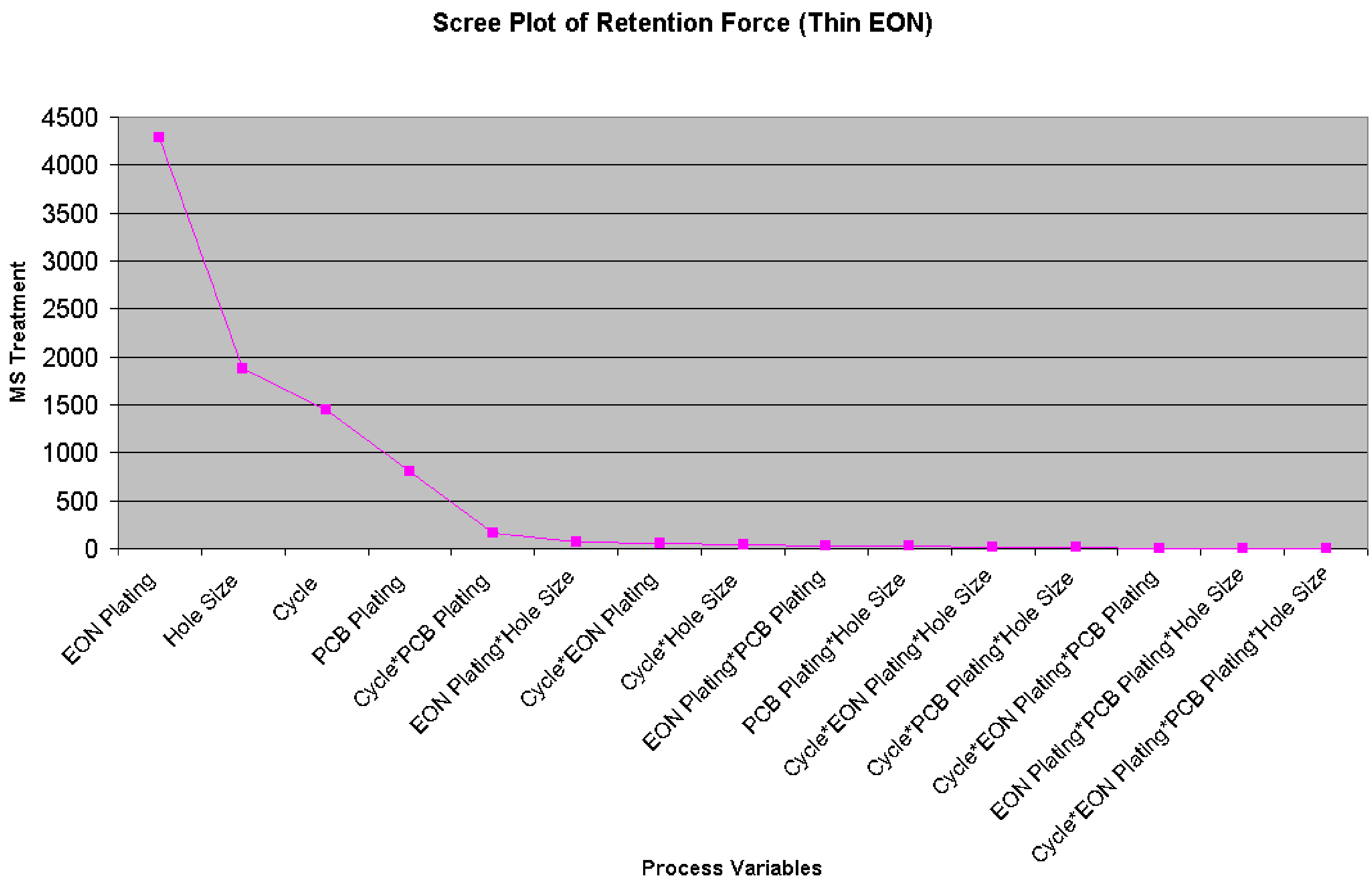
- Combined scree plots show the thin stock EON is more "robust"

Factor Analysis-Retention Force (Thick EON)



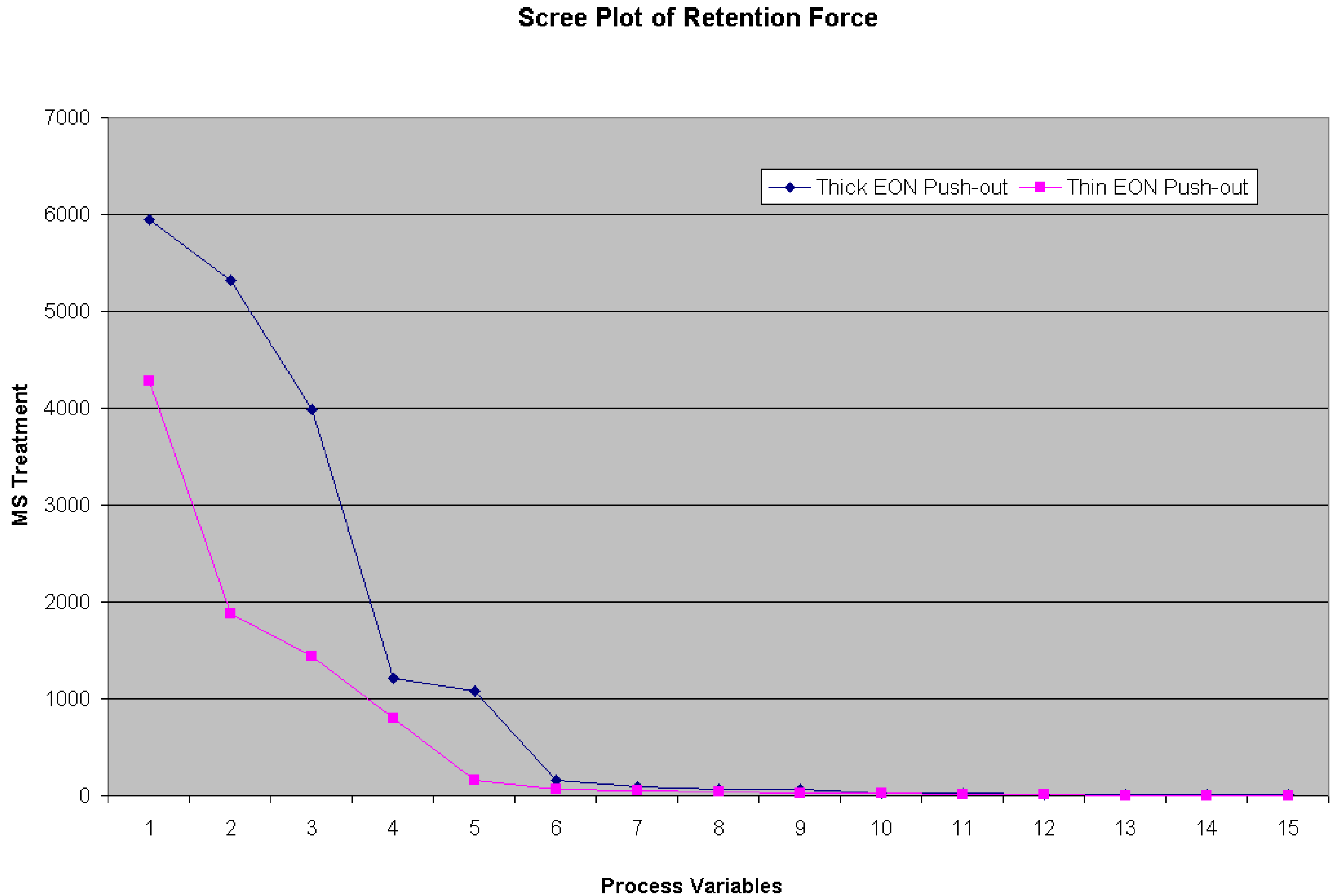
- 5 effective factors on retention force for thick stock EON
  - Pin Plating > Repair Cycle > PCB Plating > Interaction of Cycle and PCB Plating > Hole Size

Factor Analysis-Retention Force (Thin EON)



- 4 effective factors on retention force for thin stock EON
  - Pin Plating > Hole Size > Repair Cycle > PCB Plating

Factor Analysis-Retention Force

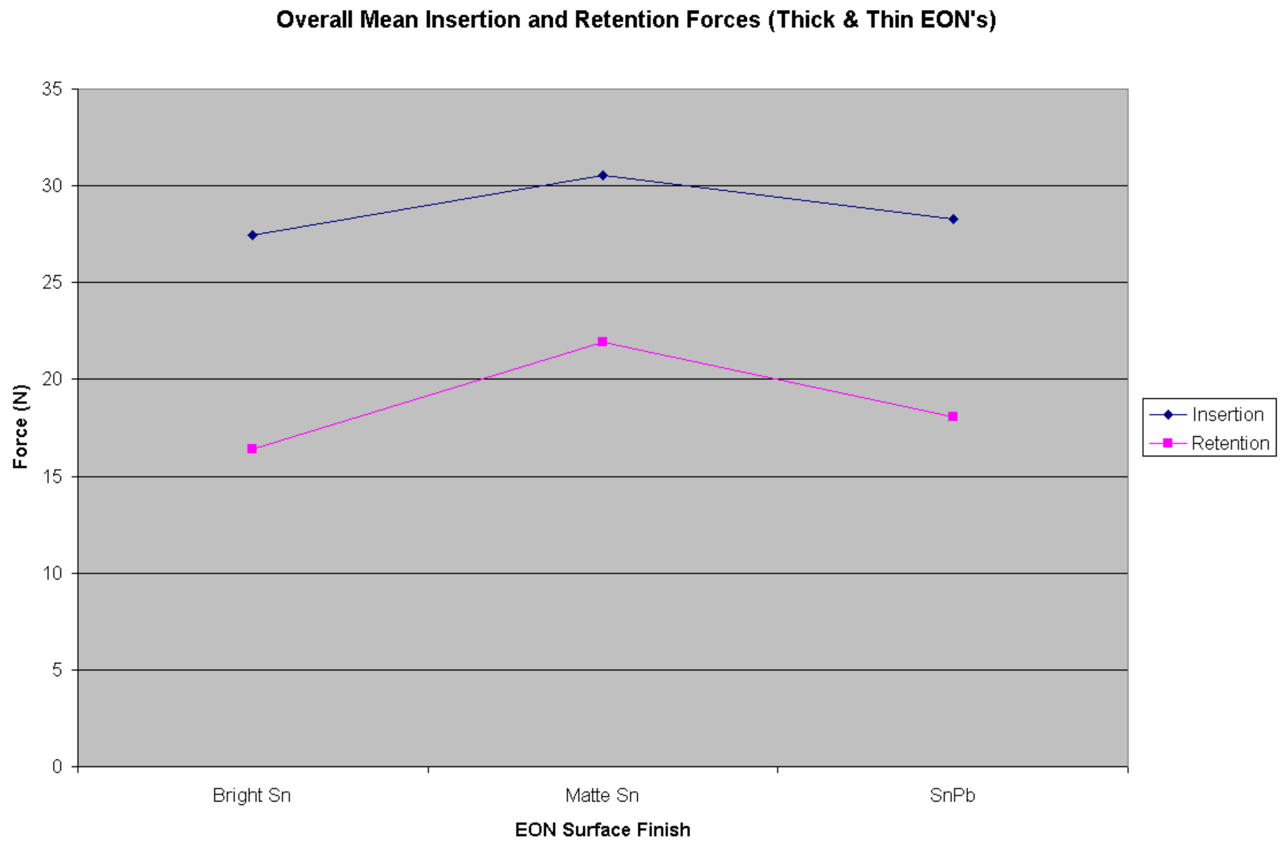


- Combined scree plots show the effective factors are “equally” affecting on both EON’s

Evidence of Material Transfer

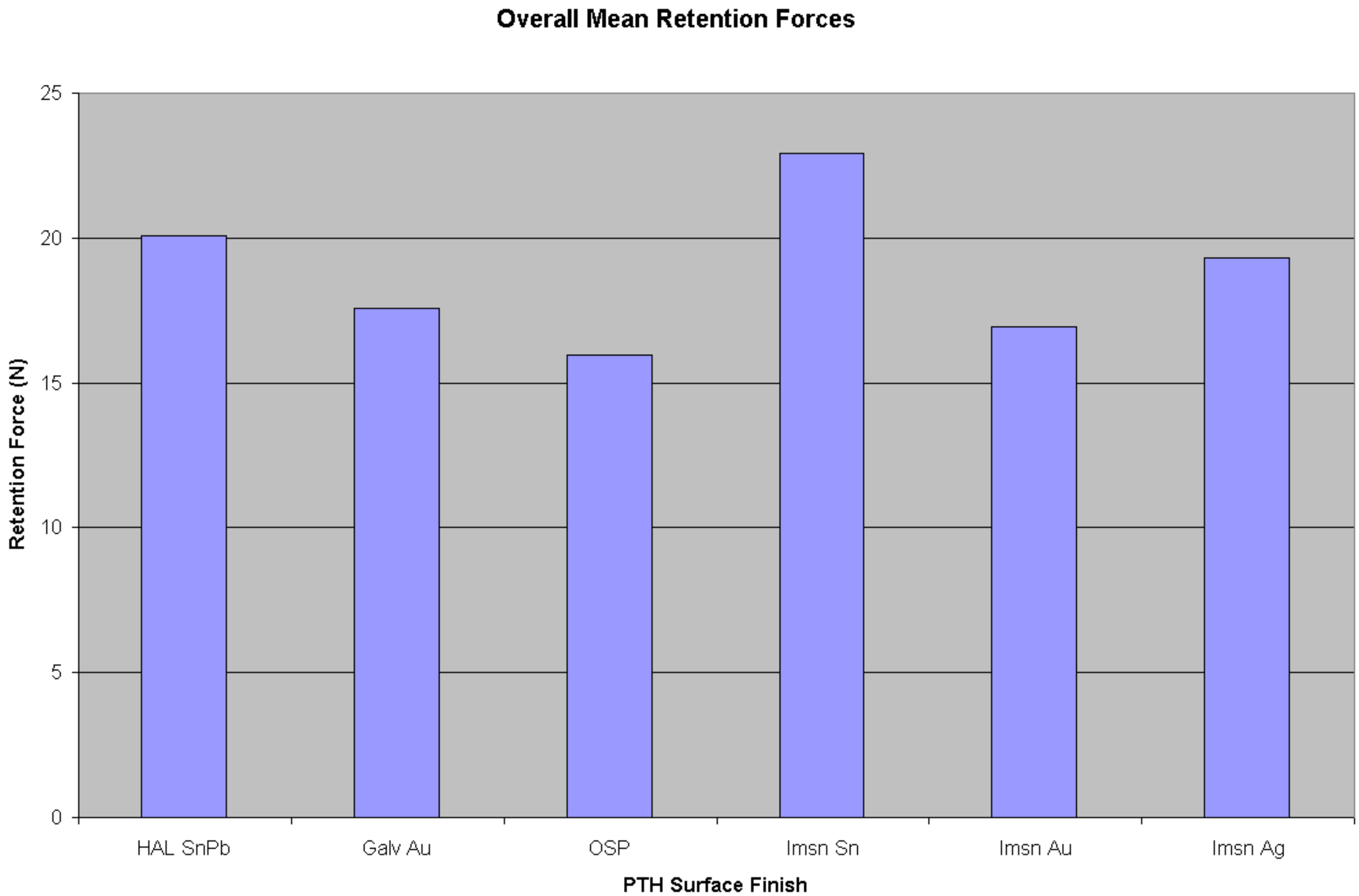
- Material transfer of soft Sn or SnPb from EON pin surface to PTH
- Reason for EON pin finish as the dominant factor for retention force?

Reliability Issues-EON Pin Finish



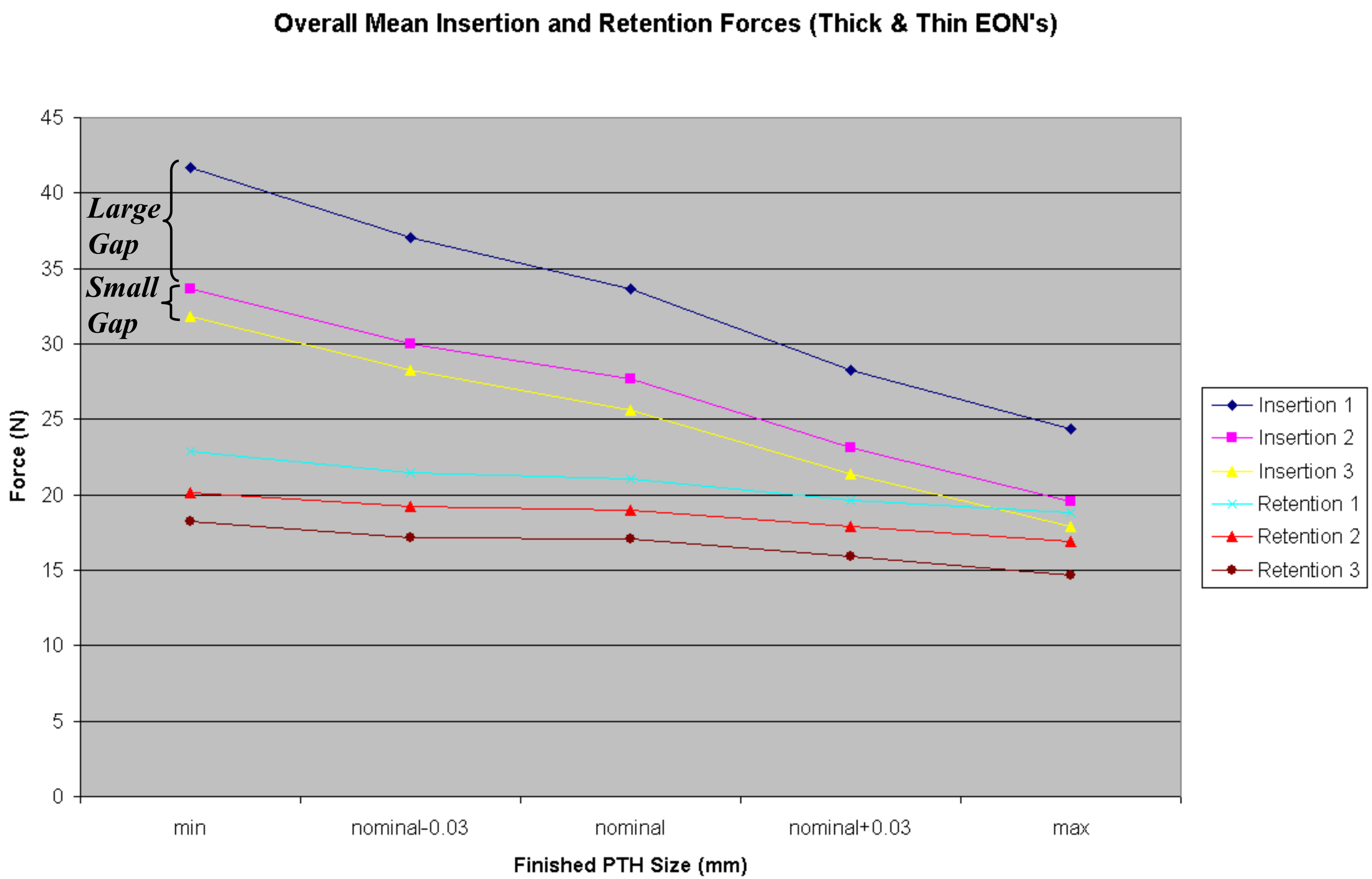
- Insertion force: matte tin (8%↑) and bright tin (3%↓)
- Retention force: matte tin (21%↑) and bright tin (9%↓)

Reliability Issues-PCB Finish



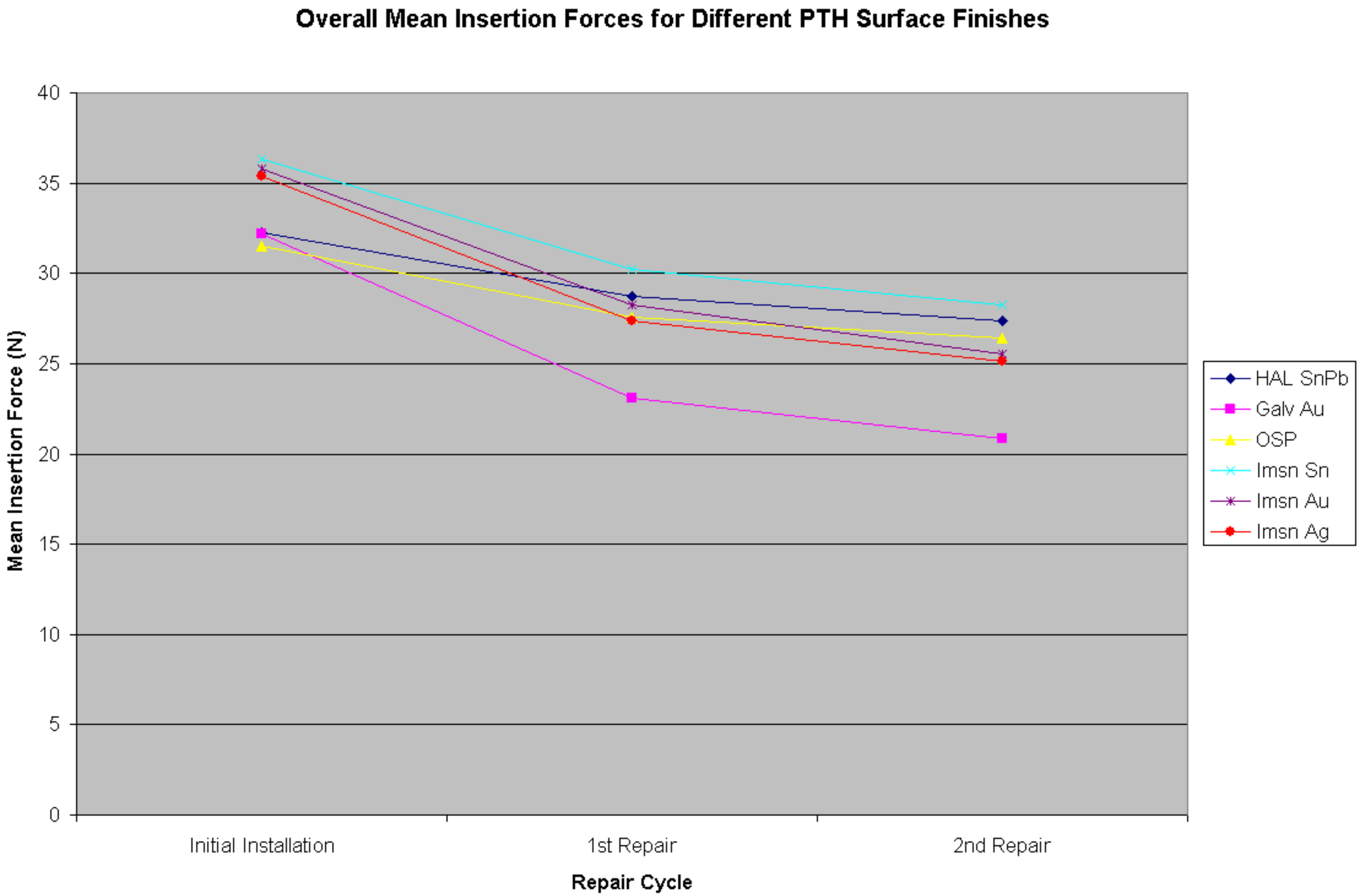
- Immersion Sn appears to provide the highest retention force
- OSP and both Au finishes are lower than HAL SnPb

Reliability Issues-PTH Size



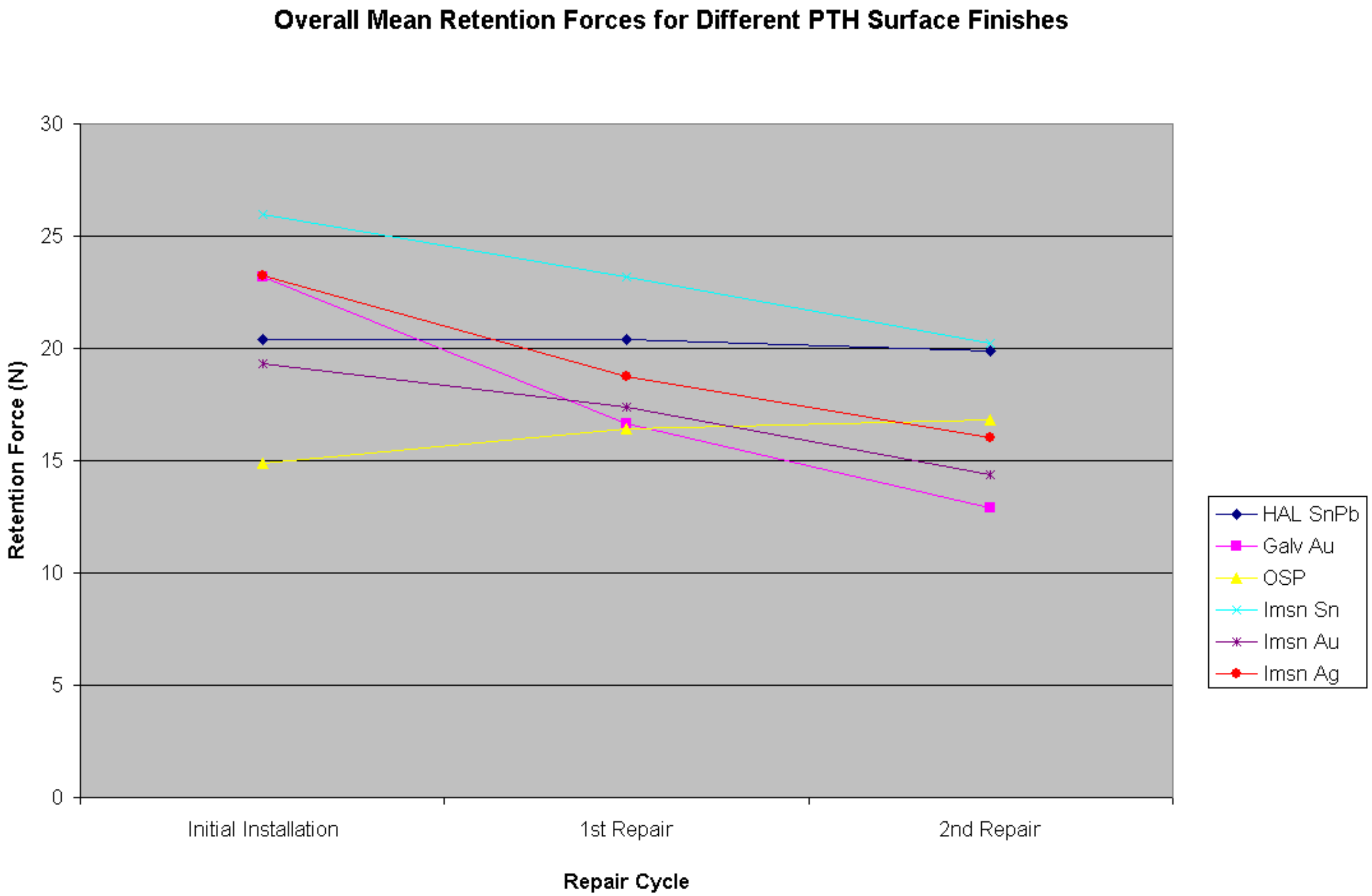
- Insertion force↑ as PTH size↓ (a invert linear function)
- Retention forces are relative flat, compared to insertion force

Reliability Issues-Repair Cycle (Insertion)



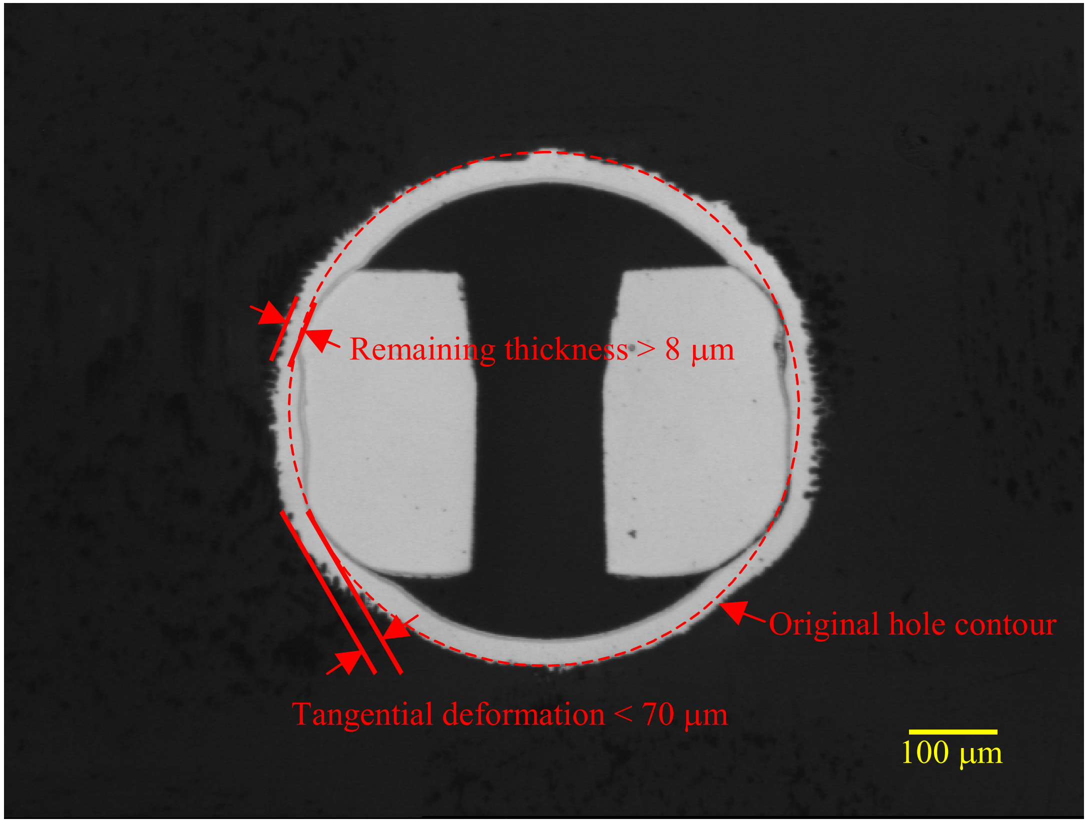
- Insertion force↓ as repair cycle↑
- Immersion Sn requires the highest insertion force
- Galvanic Au is toward the lowest

Reliability Issues-Repair Cycle (Retention)



- Retention force↓ as repair cycle↑ (for Au, immersion Sn and Ag)
- HAL SnPb keeps the same level of retention force in repairs (even increase for OSP)

Reliability Issues-PTH Damage



- Cross-sections at 0.4 mm below PCB top surface show all examined PTH's meet the IEC requirements of minimum Cu thickness and maximum tangential deformation
- Ni underplates in Au finishes are displaced due to large deformation, but the displaced surfaces are still protected by soft Sn or SnPb from material transfer

Summary

- Insertion force ($\Rightarrow$ PTH damage, housing design and pin buckling)
  - For both EON types, all four main variables in DOE are effective factors
  - PTH size is ranked no. 1 factor (PTH size$\downarrow$ $\Rightarrow$ insertion force$\uparrow$)
  - Repair cycle is no. 2 factor (no. of repair$\uparrow$ $\Rightarrow$ insertion force$\downarrow$)
  - Effects from EON and PTH finishes are minor
  - Compared to SnPb EON, 8% higher for matte tin and 3% lower for bright tin
  - For all PCB finishes, immersion Sn requires the highest force, but OSP and both Au finishes are in the lower end
- Retention force ($\Rightarrow$ normal force $\Rightarrow$ reliability)
  - For both EON's, all four main variables in DOE are effective factors
  - EON finish acts as the dominant factor
  - Compared to SnPb EON, 21% higher for matte tin and 9% lower for bright tin
  - Both lead-free pure tin finishes on EON should provide good electrical performance/reliability
  - Various lead free PCB finishes have proven viable
  - PCB finish of immersion Sn provides the highest
- All examined PHT's meet the IEC requirements of minimum Cu thickness and maximum tangential deformation
  - Ni underplate in Au finishes has high propensity to be displaced, but the displaced surface is still protected from material transfer