LET REVISE THE ASTM METHOD F.459 FOR WIREBONDING PROCESS CONTROL

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Abstract. *Wire pull testing cannot be used to monitor wirebonding process control as the X-bar and R charts of raw pull strength data routinely demonstrate wide variations. The bonding process appears to be out-of-control, indeed the testing methodology and data collection itself are inaccurate in representing the process. Many factors, which are difficult to control in production, can subtly affect the raw data SPC. The author will review the pull test method to identify the potential variation(s), that causes the errors and are misleading in the process control. The paper also includes the efforts to revise the ASTM's method F. 459 for its Pull Test in making the data collected using this method applicable in the statistic process control (SPC) chart.*

Destructive wire pull test has been used as industrial standard in testing of bond quality of the bonded wires. The pull test procedure follows the ASTM's Method F.459[1]. Unfortunately, the wire pull testing, using the ASTM's Method F.459, cannot be used to monitor process control as the X-bar and R charts of raw pull strength data routinely demonstrate wide variations and many values outside the upper and lower limit control with 3σ. The bonding process appears to be out-of-control, in deed the testing methodology and data collection itself are inaccurately in representing the process.

IDENTIFY THE POTENTIAL ERRORS IN ASTM'S METHOD F.459-PULL TEST EQUATIONS.

The objective of this paper is to examine the variables of the bond pull test theoretically and discuss the most likely sources of problems, errors inherent in the test, and the effects of the failures modes of bonded wires on pull test. In the proposed approach to the pull test, the authors will outline the process of how to improve the current equations in consideration of all the factors mentioned bellow.

Variables in Equations for Pull Force.

In order to understand the intricacies of the bond pull test, it is necessary to examine the geometrical configuration as well as the equations that define the resolution of forces.

The geometrical configuration of a bonded wire and variables are given in the figure 1[2].

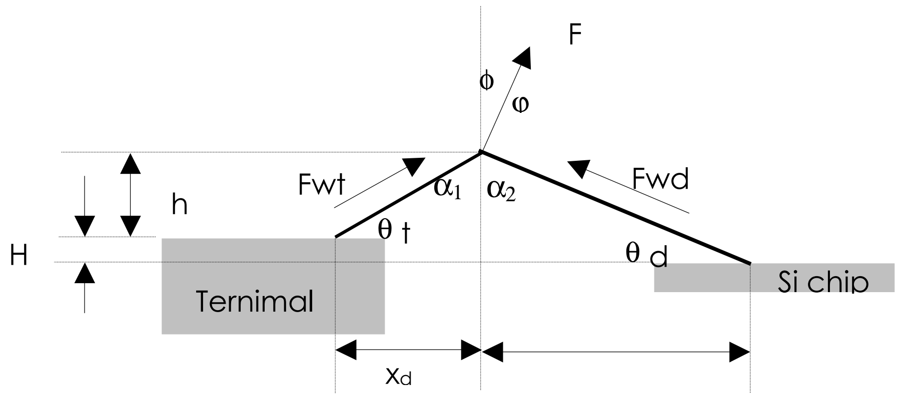

Figure 1. Geometry Variables for Wire Pull Test
in Plane of Bond Loop used in equations 1 to 3[2]

H: Bond offset

d: Bond length

h: Loop height
F_{wt}: Force applied on upper bond
F_{wd}: Force applied on lower bond
X: Hook position along bond displacement
θ_t: Angle between wire and upper bond
θ_d: Angle between wire and lower bond
ϕ: Angle pull force
φ: Angle between pull force and the plane of wire loop.
α_1, α_1: Angles between wires and vertical line

The forces in each wire at break with a specified gage pull force F is:

$$F_{wt} = F\left[\frac{\{h^2+X^2d^2\}^{1/2}\{(1-X)\cos\phi\cos\varphi+(h+H)/d\sin\phi\sin\varphi\}}{h+XH}\right] \qquad (1)$$

$$F_{wd}=F\left[\frac{\{1+(1-X)^2d^2/(H+h)^2\}^{1/2}(h+H)\{X\cos\phi\cos\varphi-h/d\sin\phi\sin\varphi\}}{h + X H}\right] \qquad (2)$$

Unfortunately, in reality, the angles ϕ ands φ of 5° to 10° may be unintentionally introduced by the bent hook. The hook positioned off the center at the position X is a common error during the pull test, then the new loop height, h', as a function of hook at the position X becomes:

$$h' = \sqrt{(h^2 + X d^2/2)/(h^2 + d^2/4) - X^2d^2} \qquad (3)$$

From these equations, the new value of h, h', will provide different values of the pull strengths, F_{wt} and F_{wd}.

Potential Errors due to Bonded Wire Configuration.

Besides the hook's position, the wire configuration is another source of errors in the pull test. The pull strength equation represents the model shown in Figure 1 can be written as:

$$F = F_w (\cos\theta_t + \cos\theta_d)^2 \qquad (4)$$

Breaking strength: $F_w = F_{wt} = F_{wd}$
Total wire length: $L = L_1 + L_2$
Wire span: d

While keeping the wire span d constant, the authors varied the total length of the wire bond L and performed the pull tests at different locations between the wire. The study showed that not only does the force vary as a function of the hook position, but it is also a function of the ratio of the wire length to the distance between the bonds (wire span).

Effects of Wire's Material Properties on the Pull Test.

Wires used for bonding processes, such as gold and aluminum wires, are ductile. They change their characteristics when subject to pull force. The stress-strain diagram is used to describe the process. They will undergo elastic deformation, then plastic deformation, and finally rupture. The stress-strain curve allows determining the dynamic aspect of the pull test. For the smaller sizes of wire, which was not annealed, their elongation has little effects on the pull force. However, for the annealed wires and heavier wires, they can have elongation of up to 10 % and 30% respectively.

Besides the annealing, which causes the reduction of pull strength, the variation in loop height during pulling, due to the elongation of the wire, will increase significantly. It in turn effects on the h/d ratio yielding a large variation in the measure of pull force.

REVISION OF THE ASTM'S METHOD F. 459 FOR THE PULL TEST

Based on the potential errors identified earlier, the task will concentrate on modifying the ASTM's Method F.459, so that it will represent the dynamics of the process, the behaviors of material under stress, and minimize errors caused by equipment and operator. As a consequence, the test procedure also may require revision in order to make it successfully applicable in the process control.

Elongation of the Bonded Wire (L)during Pull Test.

As mentioned earlier, one of the most sensitive elements of the pull test normalizing equations is the loop height. Normal practice in process control is to measure the loop height as it is, after the wire is bonded. This is one of the most common mistakes in the application of the pull test equations. Slow motion video was taken during the pull test, from the time the force applied to the moment the wire ruptured, indicates that the wire has gone through several status. Originally the bonded wire has its curly configuration. When the force is applied, the wire is stretched into the triangular shape, and goes though the elastic deformation then the plastic deformation. At the end of the plastic deformation range, the wire begins to neck out before rupture.

From the observation, the loop height has been increased from the original loop height (h_0) to the loop height (h_s) before rupture. If the wire elongation (ε), is known or accurately measured earlier and the bonded wire configuration does not varies from wire to wire, then the original loop height (h_o) and elongation (ε) can be used to calculate the true loop height (h_s) of a group of wires before rupture. It is then used to normalize the strength of each wire belonging to the group.

Loop Height (h) of the Bonded Wire Before Rupture.

True force of pull test can be calculated directly by the revised ASTM's pull test equations, which include the "dynamic" elements of the material behaviors, physical configuration of the bonded wire and the dimension of the hook into the original equations. The original ASTM's pull test equations are revised as below.

The original ASTM's equations[1] can be written as:

$F_a = F \times F_a'$ and $F_b = F \times F_b'$

F_a : True force if wire broken at the high side of the bond

F_b : True force if wire broken at the low side of the bond

F_a': Normalized coefficient if wire broken at high side of the bond

F_b': Normalized coefficient if wire broken at low side of the bond

$$F_a' = \frac{\sqrt{X^2 + h^2}}{X\dfrac{(H + h)}{(d - X)} + h}$$

and

$$F_b' = \frac{\sqrt{(H + h)^2 + (d - X)^2}}{(H + h) + \dfrac{h}{X}(d - X)}$$

The bond configuration can be properly modeled as in figure 2. Taking the elongation of the wire into consideration by replacing the measured loop height (h) with the elongated loop height (h'), just before the wire broken. Also adding the dimension of the hook (D_h) into the model. From the geometry shown by figure 2, the elongated loop height (h') can be evaluated.

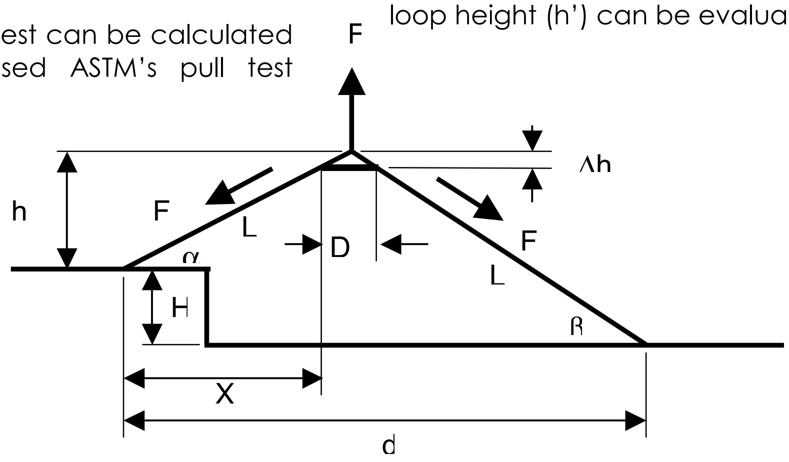

Figure 2. The Revised Pull Test Model

Let the total length of the bonded wire is L, then:

$$L = L_1 + L_2$$

where, the length of wire on the higher side of the bonded wire is:

$$L_1 = \sqrt{h_2 + X_2}$$

and the length of wire on the lower side of the bonded wire is:

$$L_2 = \sqrt{(h + H)^2 + (d - X)^2}$$

$$L = \sqrt{h^2 + X^2} + \sqrt{(h + H)^2 + (d - X)^2}$$

Value of the loop height h can be calculated as value of other elements, L, X, d and H as following:

$$h = \frac{-b + \sqrt{b2 + 4ac}}{2a} \qquad (5)$$

where: $a = (4L^2 - 4H^2)$

$b = 4HM$

$c = (M^2 - 4L^2X^2)$

Dimension of the Pull Hook.

In order to compensate the dimension of the hook, we use the values of L', X' and d' instead of L, X, and d, the equation 5 will give the value of h', where:

$L' = L - n D_h$

$X' = X - ½ D_h$

$d' = d - D_h$

n: Constant between 1.2 – 1.5

D_h: Diameter of hook

Then the corrective coefficients for the bond broken at lower end and higher ends are as following:

F_a': Normalized coefficient if wire broken at high side of the bond

$$F_a' = \frac{\sqrt{X'^2 + h'^2}}{X' \dfrac{(H' + h')}{(d' - X')} + h'} \qquad (6)$$

F_b' = Normalized coefficient if wire broken at low side of the bond

$$F_b' = \frac{\sqrt{(H' + h')^2 + (d' - X')^2}}{(H' + h') + \dfrac{h'}{X'}(d' - X')} \qquad (7)$$

PRACTICAL APPROACH IN MEASURING TRUE LOOP HEIGHT (h').

Calculate the normalized coefficient, which includes the elongation effects, to obtain the true forces of the pull tests could be time consuming. The task becomes unsuitable for day-to-day operation, especially when the wire diameter and the elongation provided by suppliers vary from lot to lot, spool to spool, and even within a spool. Using the as-provided elongation values might lead to a large variation in the SPC.

If the elongation is unknown or uncertain, and the wire configuration does not vary much from wire to wire then following procedure can be used to define the loop height h_s as shown in Figure 3:

1) Using the destructive pull test, the bonded wire is pulled so that it stretches and passes its elastic and plastic ranges, then ruptures.

2) Reading pull strength at the rupture is recorded.

3) Using the nondestructive pull test with the predetermined pull strength is set equal to 95% - 98% of the reading pull strength. The bonded wire is pulled until the predetermined pull strength is reached. Stop pulling the wire.

Note: If the bonded wire breaks before the predetermined pull strength was reached, the repeat the procedure until the nondestructive pull test is passed.

4) Measure the loop height h_s.

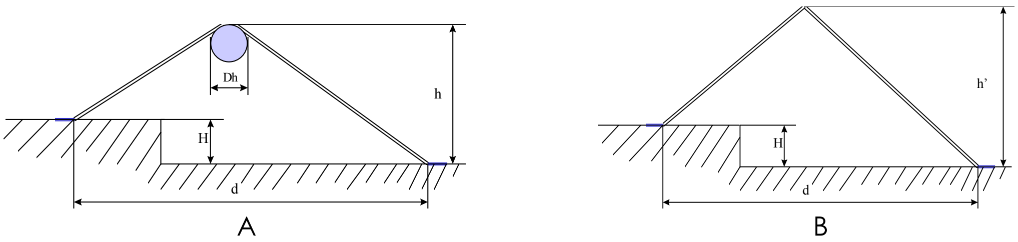

Figure 3. A: Pre-pulled wire with loop and hook.
B: Wire pulled to terminal elongation.

Note that the measured loop height (h_s) obtained using this procedure already takes the effects of the elongation into consideration. This loop height value (h_s) is very close to the loop height at rupture, since the slope of the stress-strain curve is almost flat at this range and can be used "as-is" in the ASTM equations.

EXPERIMENTAL PROVING OF THE PROPOSED APPROACHES.

In qualifying the revised ASTM equation and proposed pull test procedure, a large group of test samples will be bonded on the same wirebonder, which is tuned up to its optimum bonding condition. The samples will be divided into subgroups and wirebonded, so that they obtain similar characteristics of bond configuration, such as wire span, wire length, bond height, and loop height. All samples will be wirebonded and pull tested by same operator, using the same equipment and same bonding parameters.

Wirebonded configuration is given by figure 3, where, wire span (d) = 0.2593",

Bond step (H) = 0.0342"

During the pull test, the hook position is set accurately in order to obtain: X = ½ d

The pull test values will be normalized using the revised ASTM equations. Mean X and range R of the true force values of each sample will be treated as a data point and charted on the SPC, which was created with a larger population of wires of uniform characteristics. The procedure will be repeated for all subgroups, which represent the suspected variations in the pull test procedure and equation.

Since there is no material or process variation involved, the repeatability, if it is the case, can be considered as the repeatability of the testing procedure and the normalizing equations.

Method 1. Reading Force is "as is" in the Process Control.

In this method, all data used were the direct force readings from the pull tester. The ASTM F459 standard equations were not applied and there was no culling of data points.

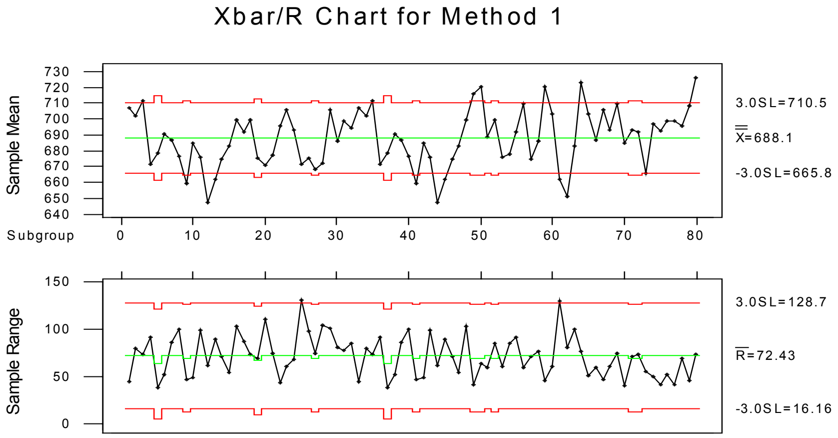

Figure 4. X-bar and R charts for Method1.

According to current SPC, thirteen (13) of 80 data points were outside 3σ indicate a process out of control. In fact is not, since the bonding process, incoming materials and equipment are under controlled and unchanged. The fact indicates that the method for measurement (pull test), its data analysis, and subsequent generation of the charts, are inadequate for process control.

Method 2. ASTM F459 Standard equations applied to raw data.

In this case, all the reading pull force were normalized using the ASTM's method 459 "as is". In this method, the loop height value (h) is the measured loop height (h_o) from the lower surface of the substrate to the top of the un-stretched loop of the wire.

Loop height:

$h = h_o$ = measured loop height = 0.1454"
Wire span: $d = d$ measured = 0.2593
Hook position: $X = ½ d$
Bond step: $H = H$ measured = 0.0342

According to current SPC, four (4) of 80 data points were outside 3σ indicate a process "out of control" and the Type I error has decreased to 5.0% (larger than 2.7% for the Type I error).

Figure 6 X-bar and R charts for Method 2. ASTM F459 transformations for true force at failure.

Method 3. Revised ASTM F459 with elongation factor

In order to include the dynamic nature of the pull test into the equations. The elongation of the wire and the nature of forces at the rupture are considered. In this case loop height, h, is calculated, where:
$L_o = 0.3755$" , measured wire length before pulling

$L = L\varepsilon = (1+\varepsilon) L_o$
$\varepsilon = 9\%$ average elongation coefficient
$d = d$ measured = 0.2593"
$X = ½ d$
$H = H$ measured = 0.0342"

In this case the loop height, h, is a value calculated from the quadratic equation, a revision to the ASTM F459 standard.

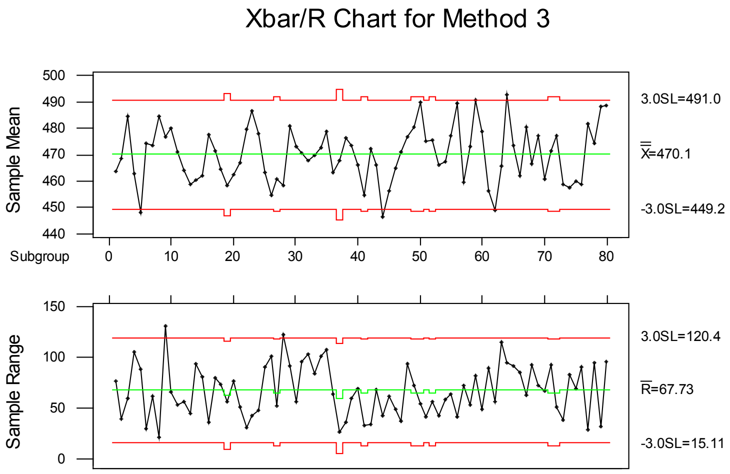

Figure 7. X and R charts for Method 3, ASTM F459 transformations with elongation

The elongation is factored into the *L* element, and subsequently is carried into equations *Fa* and Fb. The SPC chart, which represents case 3, now has three points (3) out 3σ and the Type 1 error is 3.75%. The result is not much improved and SPC is still "out of control".

Method 4: Revised ASTM incorporating the hook parameters and elongation factor.

The original ASTM's method F.459 disregarded the dimension of the hook in the wire configuration during the pull test. When the hook dimension is taken into account, then the elements, *L', X',* and *d'* replace L, X, and *d* in the equations and the calculation of Fa and Fb:

$L' = L\varepsilon - pD_h$

$X' = X - 0.5\, D_h$

$d' = d - D_h$

where: $p = 1.35$ and $D_h = 0.035$

The true forces were calculated using the revised ASTM F459 equations and with the hook parameters. In this method, the elongation factor (ε) is incorporated into the value of L'.

The SPC chart obtained, using this approach, show that two (2) data points are out 3σ. The Type I error is 2.5% (less than 2.7%), it indicates that "the process is in control". In the other word, the methodology used the pull test in the wire bonding process control is "in control".

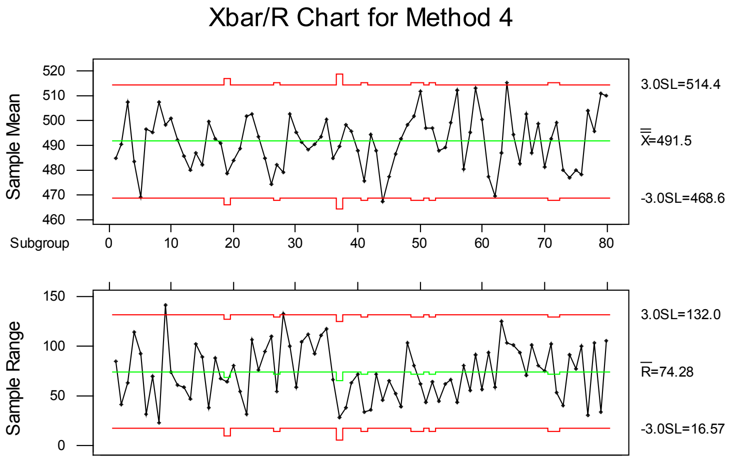

Figure 8. X and R charts for Method 4, ASTM F459 transformations with hook parameters.

Method 5: ASTM F459 incorporating Elongation by Direct Measurement.

In this method the value of elongated loop height (h_ε) is measured then replaces (h_o) in the ASTM's original method F.459 as mentioned in Method 2.

In this experiment, the elongated loop height:

h_ε = 0.1569"

and measured loop length is:

L = L_m = 0.3807"

The SPC charts created using this method (see figure 9) shows that there are 4 points out 3σ, giving a Type I error of 5.0%. Again the analysis method is suspect. But a pattern is beginning to emerge.

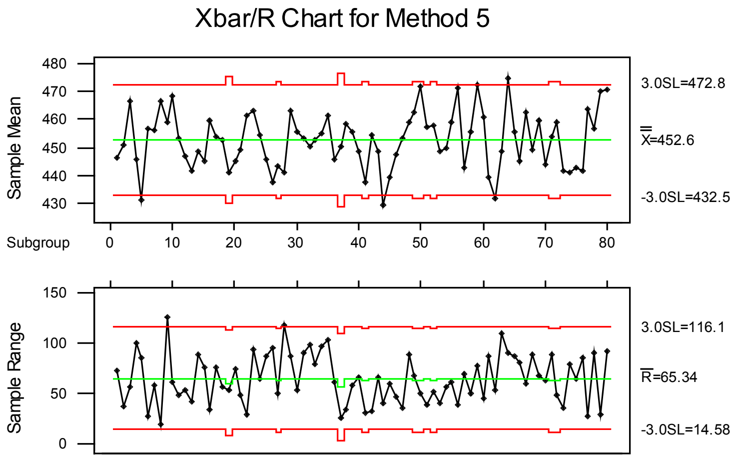

Figure 9. X-bar and R charts for Method 5, ASTM F459 incorporating Elongation Factor by Direct Measurement.

Method 6. Revised ASTM F. 459 incorporating Elongation by Direct Loop Height Measurements and Hook Parameters

When the hook parameters are considered, L', X', and d' replace L, X, and d and calculations for F_a and F_b, as described in Method 3.

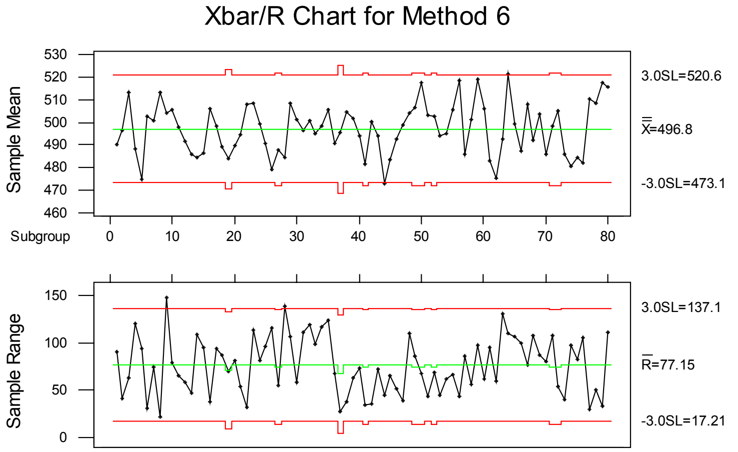

Figure 10. X and R charts for Method 6, revised ASTM F459 with direct loop height measurement and hook dimensions.

The SPC charts (see figure 10) generated from these true force values has only one (1) point out 3 σ, a Type I error of 1.25%. We now feel confident that our approach using the pull test in the wire bonding process control is acceptable.

Discussion

1. The X-bar and R charts for raw data of wire pull tests are not acceptable to monitor the wirebonding process because the testing methodology itself is out of control.
2. The use of the ASTM F459 standard equations will decrease the Type I error caused by the data collection and measurement (true force), however it still is greater than 2.7% for a two-sided 3σ limit process and is not acceptable.
3. The revised ASTM F459 equations further decrease the Type I error, yet not into the acceptable range. When the hook parameters are incorporated into the revised ASTM F459 equations, the Type I error is decreased to a value where we can be confident that the analysis process reflects the true forces.

CONCLUSION.

From the experiment data, we can conclude that many factors, which are difficult to control in production, can subtly affect the raw data SPC (Statistical Process Control). Such factors include consistency of wire diameter, purity of the wire alloy, doping dispersion, substrate and die consistency, and many other issues.

Table 2. Comparison of Analysis Results for X-bar Charts

	Mean Force	**Std Deviation**	**Range Spread**	**Points out 3 σ**	**Type I Error**
Method 1	688.1	.47	112.54	13	16.0%
Method 2	464.6	6.97	105.28	4	5.0%
Method 3	470.1	6.97	105.29	3	.75%
Method 4	491.5	7.63	115.43	2	.5%
Method 5	452.6	6.73	101.52	4	5.0%
Method 6	496.8	.93	119.89	1	1.25%

The ASTM recognized that force coefficients were needed to determine the true failure force relevant to the failure location. They developed the current ASTM F459 to determine the true failure forces, Fa and Fb. Although these equations certainly decrease the variation and decrease the number of points outside 3σ, they ignore the dynamic characteristics of the wire loop configuration during the pull tests. The analysis has shown that use of the revised ASTM F459 equations with hook parameters will calculate the true pull forces in pull testing with an acceptable Type I error and is suitable to be used for the process control of the wirebonding production line.

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