Capability Assessment for Weibull In-Cell Touch Panel Manufacturing Processes With Variance Change

Yu-Ting Tai, Wen Lea Pearn, Kai-Bin Huang, and Lu-Wei Liao

***Abstract*—Since touch panels can provide natural user-interface, including fluent multipoint touch or advance gesture recognition, recently they have been extensively applied in various portable devices, such as smart phones and tablet PCs. In-cell touch panel is the highest integration touch technology as compared to the on-cell and typical touch panel manufacturing technologies for the thinnest and lightest structure. In in-cell manufacturing processes, manufacturing yield assessment is an essential issue. However, inevitable process variance changes could arise from equipment, material, and operation, and may not be detected within a short time. In addition, the process output usually has a Weibull distribution. To circumvent the undetected variance change causing the inaccurate manufacturing yield calculation, we provide a yield measure index to avoid overestimating when the underlying distribution is Weibull with variance change. We also show that the accommodation of the process capability index would not be affected by the scale parameter of Weibull distribution. Applying this method, the magnitudes of the undetected variance change are incorporated into the evaluation of manufacturing yield. For illustration purposes, a real application in an in-cell manufacturing factory, which is located in the Science-based Industrial Park in Hsinchu, Taiwan, is presented.**

***Index Terms*—In-cell touch panel, manufacturing yield, variance change, weibull distribution.**

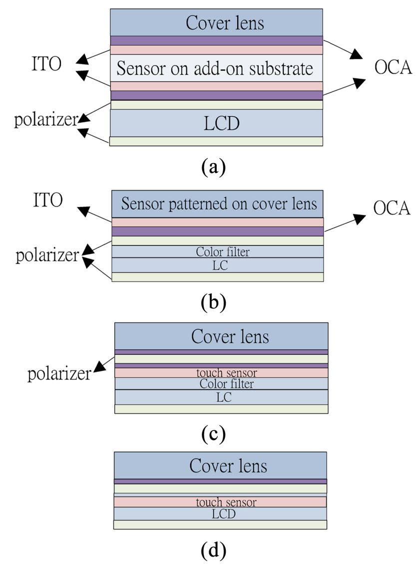

Fig. 1. Diagrams of touch panel product types. (a) Add-on touch panel type. (b) OGS touch panel type, (c) On-cell touch panel type. (d) In-cell touch panel type.

I. INTRODUCTION

IN RECENT years, touch panels have been extensively applied in various portable devices such as smart phones and tablet PCs since they provide a natural user-interface (NUI) to enter information easily and intuitively [1]. Capacitive sensors dominate touch applications due to better user experience, including fluent multi-point touch or advance gesture recognition. There are different capacitive touch panel technologies according to the stack-up of the touch sensor. One of these technologies is add-on type, including GG (glass-glass), GFF (glass–film-film), G1F (glass-film), and OGS (one glass solution). Sensor for add-on touch panel is patterned on glass or film substrate, being so-called GG, GFF, G1F, or OGS. This sensor is laminated between cover lens and LCD via optically clear adhesive (OCA) by lamination process. Another touch technology is embedded type, which is dominated by LCD makers. They are on-cell and in-cell touch technologies. For on-cell type, the touch sensor is patterned between the polarizer and color filter layer. For in-cell type, the touch sensor is integrated into LCD stack by sharing LCD process. No matter which touch sensor type, all the touch electrode can be made by indium tin oxide (ITO), a transparent and conductive material. Fig. 1 shows the add-on sensor and embedded sensor on Fig. 1(a) to Fig. 1(d), respectively.

New structures of substrate involving OGS and in/on-cell have no need of extra sensor substrate due to integration. The three touch panel types take advantage of cover lens and display's parts for patterning and they can reduce lamination process which is touch panel module makers' major loss. In-cell touch panel type is the highest integration touch

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technology comparing to the other two, since it shares LCD manufacturing process or even same LCD stacks. It performs the thinnest and lightest structure, so that has become new trend for fantastic user experience. Since the in-cell touch panel being an essential part of the portable devices in current and future trend, the manufacturing yield assessment of the in-cell touch panel is a very important issue.

In the in-cell touch panel manufacturing process, ITO (Indium Tin Oxide) thin film patterning is one of the essential operations in which the photolithography and etching manufacturing steps are involved. ITO thin films have been commonly constructed as the transparent electrodes due to excellent photoelectrical properties. It should be noted that surface resistance is a very critical specification which is mainly depended on the manufacturing capability of the electrodes. It needs uniform surface resistance to obtain uniform touching performance.

As high quality requirements of the portable devices, the stringently control for surface resistance in in-cell touch panel manufacturing processes are required. In in-cell touch panel manufacturing factories, control charts are commonly applied to provide early warning for the changes in the process mean and variance for the critical specification. Yield measure index is usually used to assess the manufacturing yield. However, inevitable process variance changes which could arise from equipment, material, and operation, and may not be detected within short time. Manufacturing yield may be overestimated due to the inevitable process variance changes. In addition, the process output usually has a Weibull distribution. In this paper, we develop a yield assessment formula to obtain Weibull in-cell touch panel manufacturing yield more accurately, as it could provide feedback to in-plant practitioners on what actions need to take for manufacturing yield control and improvement.

The remainder of the paper is organized as follows. The manufacturing yield problem of in-cell touch panel manufacturing process is presented in Section II. In Section III, we present the manufacturing yield assessment using a yield measure index method and present the statistical properties of sample variance for Weibull in-cell touch panel manufacturing processes. In addition, we present a manufacturing yield assessment to accommodate undetected variance changes. We also show the accommodation of the process capability index would not be affected by the scale parameter of Weibull distribution. To illustrate the applicability of the proposed manufacturing yield assessment, a real-world case taken from the manufacturing process in an in-cell touch panel manufacturing factory is shown in Section IV. Finally, Section V provides the conclusions.

II. In-Cell Touch Panels Manufacturing Yield Problem

In-cell touch panel manufacturing technologies have attracted many practitioners to devote their efforts since in-cell touch panels allow for slimmer and lighter devices as well as improve backlight penetration for brighter displays which are extensively applied in the high-end devices recently. Since the touch sensor is integrated into LCD stack by sharing LCD process, the touch electrodes are made by ITO (Indium Tin Oxide) thin film in the LCD array manufacturing process. Thus, the photolithography operation and etching operation are used to form the pattern of touch electrodes on the thin film. Fig. 2 shows the sensing ITO lines (brown) and driving ITO lines (green).

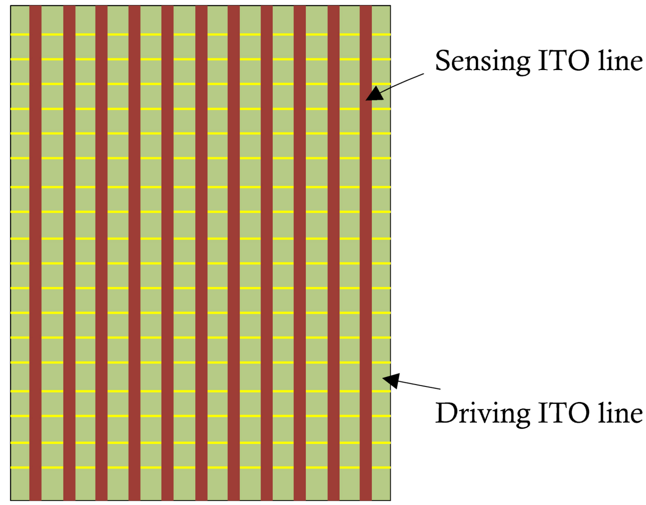


Fig. 2. Diagram of electrode.

In the manufacturing process of forming the pattern of touch electrodes, it is noted that surface resistance is an essential specification. It needs uniform surface resistance to obtain uniform touching performance. Higher or lower resistance degrades touch and display performance since touch sensing signal is synchronized with periodic display signal. When resistance value changes, the synchronization between touch and display operation have been changed. Some touch panel controller could compensate un-uniform surface resistance, but the cost increases. It is indeed that touch panel maker should be compliant to the resistance specification in order to increase manufacturing yield.

In the in-cell touch panel manufacturing process, inappropriate photolithography or etching operations may cause over- or insufficient etching. When some defects occur in the ITO patterning operation, the malfunction of display (such as bridge and short) is accompanied. These situations may cause the negative side effect that is the un-uniform surface resistance may raise and the variance of surface resistance may change. Notably, data of surface resistance collected from shop floor is skewed distributions that are bounded on one side occur frequently in industry, since open or short electrodes may cause the resistance raise dramatically. It is better described by Weibull than by normal distribution. Weibull distribution is a very flexible distribution and can easily be fit to many data sets. In addition, while the integration of the touch sensor into the LCD stack by sharing the LCD manufacturing process, the difficulties of the manufacturing technology raise and some inevitable process variations regarding inadequate electrodes may occur owing to the limitations of equipments, materials, and workmanship may not be detected within short time. To avoid overestimating

TABLE I
CORRESPONDING YIELD AND NCPPM FOR VARIOUS VALUES OF YIELD MEASURE INDEX

C_{pk}	Yield	NCPPM
1.0	0.997300204	2699.796
1.2	0.999681783	318.217
1.33	0.999933927	66.073
1.4	0.999973309	26.692
1.6	0.999998413	1.587
1.67	0.999999456	0.544
1.8	0.999999933	0.067
2.0	0.999999998	0.002

the manufacturing yield and successfully implement any corrective action for quality improvement programs, we present a modified yield measure index in this paper.

III. CAPABILITY INDEX APPROACH FOR IN-CELL TOUCH PANEL MANUFACTURING YIELD ASSESSMENT

Manufacturing yield has been the most basic and critical criterion used in the manufacturing industry for measuring process performance. Since the fiercer competition in global portable devices market, such as smartphone and tablet PC, manufacturing yield assessment for in-cell touch panel processes is very important. It is noted that typical yield measure index is applied to assess manufacturing yield under stable normal process (Montgomery [2], Pearn and Kotz [3]). However, surface resistance data collected from shop floor is better described by Weibull than by normal distribution and undetected variance changes may occur. Consequently, typical yield measure index may not be applied directly.

A. Manufacturing Yield for Stable Normal Process

In many in-plant applications, yield-based index C_{pk} is commonly used as an effective tool to assess manufacturing yield, which can provides bounds of the process yield for a normally distributed process with a fixed value of C_{pk}. This approach can measure the process departures from the target value and the magnitude of process variance. The index C_{pk} proposed by Kane [4] and defined as $\min\{(USL-\mu)/3\sigma, (\mu-LSL)/3\sigma\}$, where USL and LSL are the upper and lower specification limits, respectively; μ is the process mean and σ is the process standard deviation. Table I presents various commonly used capability requirement and the corresponding overall process yield associated with non-conformities (NC in parts per million, NCPPM).

In Table I, it is no more than 2700 NCPPM while the value of C_{pk} is equal to 1. As the value of C_{pk} is equal to 1.33, the defect rate drops to 66 ppm. To attain less than 0.002 ppm defect rate, a C_{pk} value of 2.00 is required (see Montgomery [2]).

B. Manufacturing Yield for Weibull in-Cell Touch Panel Manufacturing Process with Undetected Variance Changes

In-cell touch panel is a Weibull-distributed process with undetected variance changes resulting from the limitations of equipments, materials, and workmanship. However, typical yield-based index C_{pk} has two essential assumptions that are the process is in a state of stable and normal. Bothe [5] considered mean shifts and Pearn *et al*. [6] investigated the variance changes for normal processes, respectively. However, the in-cell touch panel manufacturing process is not approximately normal-distributed. In addition, Hsu *et al*. [7] and Pearn *et al*. [8] investigated mean shifts and variance changes for Gamma manufacturing process environments, respectively. In fact, in many real situations, the surface resistance data collected from some in-cell touch panel shop floors are Weibull-distributed. It should be noted that Weibull distribution, with various values of α and β, is a very flexible distribution and can cover a wide class of non-normal applications in the industry (Rinne [9]).

The Weibull distribution can be denoted as Weibull (α, β) with cumulative distribution function and the probability density function given by

$$F_X(x) = 1 - \mathrm{e}^{-(x/\alpha)^\beta},\ x \geq 0,$$

and

$$f(x) = \beta\alpha^{-\beta}x^{\beta-1}e^{-(\frac{x}{\alpha})^\beta},\ x \geq 0,$$

where $\alpha(>0)$ is the scale parameter, and $\beta(>0)$ is the shape parameter. The mean and variance of Weibull distribution are

$$\mu = \alpha[\Gamma(1+\beta^{-1})]$$

and

$$\sigma^2 = \alpha^2\left[\Gamma(1+2\beta^{-1}) - \Gamma^2(1+\beta^{-1})\right],$$

respectively. As it can be seen in Fig. 3, the Weibull distribution covers a wide class of non-normal applications.

1) *Stability Control Using S^2 Chart for Weibull in-Cell Touch Panel Process:* Control chart is widely used to identify shifts or drifts in processes. In this paper, we investigate the effects on the manufacturing yield assessments for in-cell touch panel manufacturing process in which the manufacturing data is a Weibull distribution with undetected variance change. The S^2 control chart is a common and effective tool to monitor process variability. However, when we apply the control chart, some essential assumptions should be satisfied, such as the process characteristics must follow normal distribution. Since the in-cell touch panel process investigated in this paper is Weibull-distributed, violating the assumption, we need to replace the traditional upper and lower control limits, $\left(\bar{S}^2/n-1\right)\chi^2_{\alpha/2,n-1}$ and $\left(\bar{S}^2/n-1\right)\chi^2_{1-(\alpha/2),n-1}$, as quantiles of the cumulative distribution function from different parameters of Weibull $(\alpha,\ \beta)$, where $\bar{S}^2$ is an unbiased estimator of σ^2.

It should be noted that the explicit close forms regarding the probabilities of detecting variance change using the S^2 control chart are rather complicated for Weibull-distributed data. To avoid overestimating manufacturing yield, we suggest the power of the S^2 chart for in-cell touch panel Weibull-distributed data based on the UCL and LCL be obtained using the simulation technique. In the paper, to investigate the behavior of sampling distribution of variance for Weibull data and determine the estimated upper and lower control limits, the Monte-Carlo simulation method is applied. Three steps of

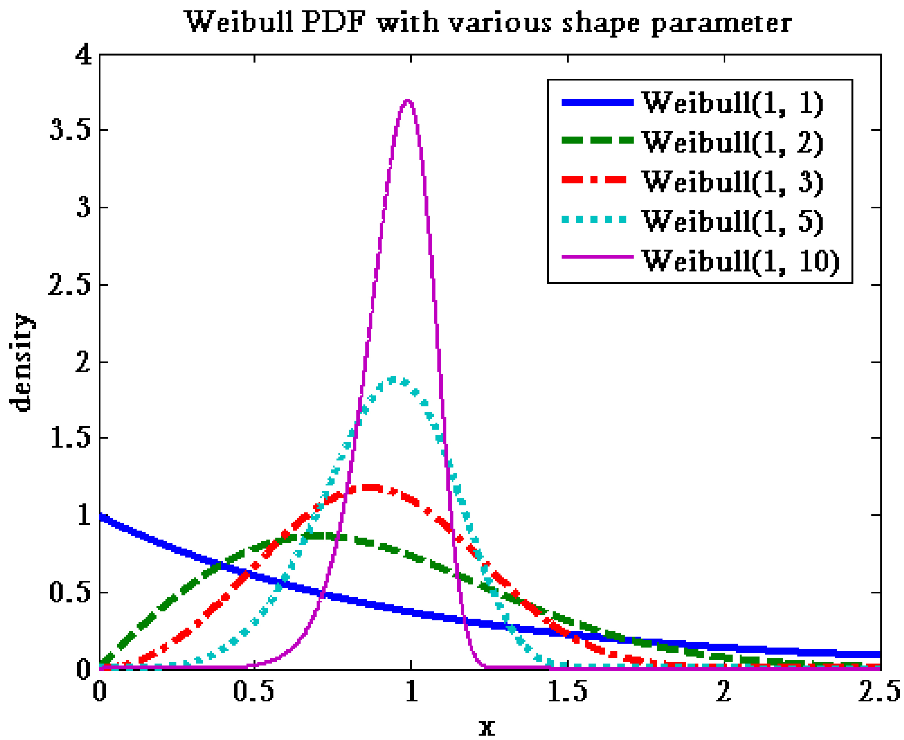


Fig. 3. Probability density functions for Weibull distribution with different parameter combinations.

the Monte-Carlo algorithm to determine the control limits of S^2 control chart are summarized as follows:

Step1: Generate N preliminary samples from Weibull (α, β), each of size k. Let S_i be the variance of the ith sample.

Step2: Sort S_i and obtain $S_{(1)}<S_{(2)}<\ldots<S_{(N)}$. Let $\hat{t}_p$ be the percentile for S_i.

Step3: Calculate the $\hat{t}_{0.99865}$ and $\hat{t}_{0.00135}$. Let $\hat{t}_{0.99865}$ be the upper control limit and $\hat{t}_{0.00135}$ be the lower control limit for Weibull (α, β).

Applying the Monte-Carlo approach, we can obtain the UCL and LCL. Then, the power of S^2 for Weibull process data is derived. Type II error β is

$$\begin{aligned}\beta &= P\left(LCL \le S^2 \le UCL | \sigma_1 = k\sigma_0\right)\\ &= P\left(F_{0.00135} \le S^2 \le F_{0.99865} | \sigma_1 = k\sigma_0\right)\\ &= G_{S^2}\left(F_{0.99865}\right) - G_{S^2}\left(F_{0.00135}\right),\end{aligned}$$

where $1-\beta$ is the detection power of the process and σ_1 is the new standard deviation after the variance change (σ_0 is the standard deviation of the original process). In addition, $G_{S^2}(\cdot)$ represents the empirical cumulative distribution function of sample variance from Weibull distribution with variance change. The $F_{0.99865}$ and $F_{0.00135}$ are the percentile points of the cumulative distribution function (CDF) of the Weibull-distributed process. The control limits LCL and UCL are calculated as $F_{0.00135}$ and $F_{0.99865}$, respectively.

We develop a MATLAB program to compute the probability of process variance out of control limits. When process variance changes from σ^2 to $(k\sigma)^2$ and mean is fixed, the parameters α and β will change to new parameters α' and β'. We can obtain the detection power under the situation that the process variance changes. The parameters α' and β' can be obtained using the following steps:

Step1: Assume the new standard deviation $\sigma_1 = k\times\sigma$, and k, μ, and σ are all known.

Step2: The mean and variance of Weibull distribution are $\mu = \alpha[\Gamma(1+\beta^{-1})]$ and $\sigma^2 = \alpha^2[\Gamma(1+2\beta^{-1}) - \Gamma^2(1+\beta^{-1})]$. Then, we compute σ_1 divided by μ as follows:

$$\begin{aligned}\frac{\sigma_1}{\mu} &= \frac{\sqrt{\alpha^2[\Gamma(1+2\beta^{-1}) - \Gamma^2(1+\beta^{-1})]}}{\alpha[\Gamma(1+\beta^{-1})]}\\ &= \frac{\sqrt{[\Gamma(1+2\beta^{-1}) - \Gamma^2(1+\beta^{-1})]}}{[\Gamma(1+\beta^{-1})]}.\end{aligned}$$

Step3: The new scale parameter (α') and shape parameter (β') can be obtained.

Table II shows the detection power when the surface resistance data of an in-cell touch panel process is Weibull-distributed and $\alpha = 1$ as well as β =3, 4, and 5. The various magnitudes of variance change in σ are 1.0(0.5)3.5. In Table II, it should be noted that for the S^2 chart with sample subgroup size $n = 9$ in Weibull (1,5), the chance of catching a σ_0 variance change would only 0.26 percent. Such low probabilities indicate that small changes of variance may not be detected within short time in in-cell touch panel manufacturing process.

2) *Manufacturing Yield Assessment:* For the Weibull in-cell touch panel manufacturing processes with variance change, to circumvent the undetected variance change causing the incorrect manufacturing yield calculation, we consider the magnitude of standard deviation change. AS_{50} is the magnitude of standard deviation change we need to accommodate when the detection power is fifty percent. In this paper, we set

TABLE II
DETECTION POWERS OF THE S^2 CHART FOR VARIOUS WEIBULL DISTRIBUTIONS WITH VARIOUS SAMPLE SUBGROUP SIZES

	change in σ	subgroup size n				
		9	10	11	12	13
Weibull(1,3)	1	0.0027	0.0029	0.0027	0.0027	0.0028
	1.5	0.2373	0.2635	0.2886	0.3166	0.3416
	2	0.5804	0.6237	0.6631	0.7009	0.7352
	2.5	0.7266	0.7647	0.8002	0.8307	0.8565
	3	0.7804	0.8163	0.8463	0.8722	0.8940
	3.5	0.8004	0.8335	0.8610	0.8849	0.9045
Weibull(1,4)	1	0.0026	0.0028	0.0026	0.0027	0.0028
	1.5	0.2399	0.2707	0.2975	0.3257	0.3576
	2	0.6445	0.6928	0.7335	0.7704	0.8063
	2.5	0.8149	0.8530	0.8825	0.9072	0.9272
	3	0.8759	0.9052	0.9276	0.9449	0.9585
	3.5	0.8984	0.9234	0.9423	0.9564	0.9677
Weibull(1,5)	1	0.0026	0.0026	0.0027	0.0027	0.0028
	1.5	0.2164	0.2418	0.2721	0.2978	0.3295
	2	0.6508	0.6995	0.7459	0.7822	0.8177
	2.5	0.8485	0.8835	0.9123	0.9326	0.9502
	3	0.9168	0.9397	0.9580	0.9703	0.9792
	3.5	0.9417	0.9592	0.9723	0.9807	0.9871

the detection power is equal to 0.5 since the most common industrial applications are to set average run length to 2. In addition, we develop a MATLAB program to compute the accommodation for various variance changes. We fix detection power which can be shown as $P\left(LCL \le S^2 \le UCL \;|\sigma_1 = k\sigma_0\right) = 0.5$ and find k. Tables II and IV display the magnitude of standard deviation change (AS_{50}) in which data come from various Weibull $(1, \beta)$ distributions for various values of $\beta = 1(1)24$ and $n = 10(1)32$.

In Table III, we can find that if β is 3 with $n = 10$, the value of AS_{50} is 1.785. When $\beta = 1$, AS_{50} are all greater than 2.5. It can be found that changes in σ smaller than $AS_{50}\sigma$ would likely be missed. Consequently, AS_{50} would be the marginal size of the undetected standard deviation change we should accommodate.

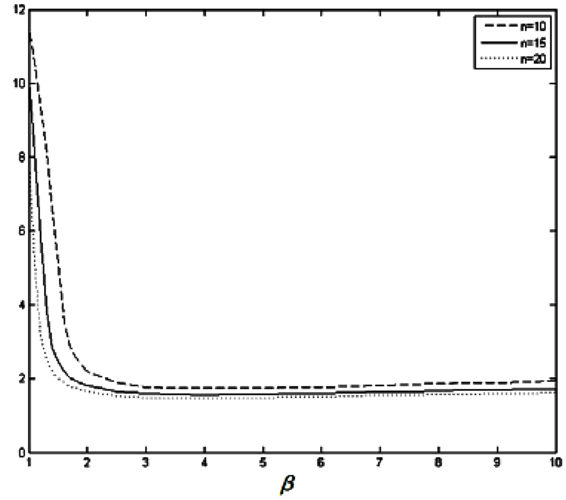
3) *Discussion:* It is particularly noted that the calculation of AS_{50} would not be affected by the scale parameter (α) of a Weibull distribution. In the paper, we apply a cubic polynomial approximation method provided by Lu [10]. The essential idea of the cubic polynomial approximation method is to use the three quantiles to approximate the sum of multiple Weibull distributions. Applying a cubic polynomial approximation method, we can compute the probability of $\bar{X}_n$ when $X_1, \ldots, X_n$ is a random sample from Weibull (α, β), and if we let $Y_i = X_i/\alpha$ then we have $Y_i = X_i/\alpha \sim$ Weibull$(1,\beta)$ and

$$\bar{Y} = \frac{\sum_{i=1}^{n} Y_i}{n} = \frac{\sum_{i=1}^{n} (X_i/\alpha)}{n} \sim \text{Weibull}\left(\frac{1}{n}, \beta\right). \quad (1)$$

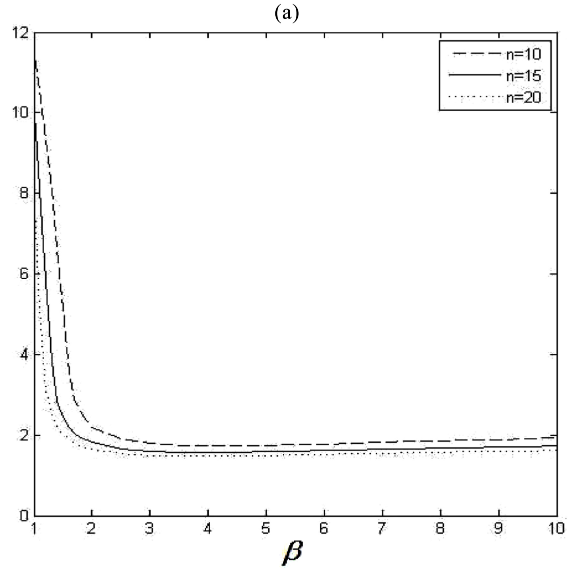
From Eq. (1) we can obtain

$$P\left\{LCL \le \bar{X} \le UCL\right\} = P\left\{\frac{LCL}{\alpha} \le \bar{Y} \le \frac{UCL}{\alpha}\right\} \\ = P\left\{F_{\bar{X}(0.00135)} \le \bar{X} \le F_{\bar{X}(0.99865)}\right\}. \quad (2)$$

The control limits LCL and UCL are calculated as $F_{\bar{X}(0.00135)}$ and $F_{\bar{X}(0.99865)}$ are 0.135^{th} and 99.865^{th} percentiles



(a)



(b)

Fig. 4. The AS_{50} curves of the Weibull process with different α values for various n values on the horizontal. (a) α = 1. (b) α = 3.

of $\bar{X}$ of sampling distribution. We can obtain the approximate CDF of $\bar{X}$ distribution which Lu [10] provided. Consequently, from Eq. (2), without loss of generality, we can set α = 1 to obtain the value of AS_{50}. We can infer the accommodations in standard deviation change, AS_{50}, would not be affected by the scale parameter α. Fig. 4 depicts the AS_{50} curves of the two Weibull processes with scale parameters $\alpha = 1$ and $\alpha = 3$ for subgroup sizes $n = 10$, 15, and 20. It can be seen that the magnitude of standard deviation change would not change for α values.

C. Manufacturing Yield Calculation

It is noted that in-cell touch panel manufacturing process is better described by Weibull-distributed. In addition, manufacturing yield may be overestimated due to inevitable process variance changes. Chen and Pearn [11] considered come generalizations of these basic capability indices to cover non-normal distributions. In the non-normal case, if we are able to find a better distribution from the data, which provides a satisfactory fit, we can obtain more accurate measures of the

TABLE III
AS_{50} VALUES FOR VARIOUS SUBGROUP SIZE n AND β =1(1)12

	Weibull distribution(1, β)												
n	(1,1)	(1,2)	(1,3)	(1,4)	(1,5)	(1,6)	(1,7)	(1,8)	(1,9)	(1,10)	(1,11)	(1,12)	N(0,1)
10	11.563	2.195	1.785	1.729	1.748	1.779	1.824	1.861	1.896	1.934	1.967	1.998	1.802
11	11.250	2.078	1.727	1.688	1.699	1.740	1.771	1.814	1.847	1.884	1.904	1.941	1.755
12	11.094	1.984	1.689	1.646	1.670	1.695	1.736	1.770	1.799	1.834	1.861	1.887	1.716
13	10.660	1.914	1.656	1.618	1.635	1.665	1.699	1.731	1.764	1.795	1.824	1.848	1.682
14	10.195	1.857	1.617	1.592	1.605	1.637	1.670	1.705	1.734	1.759	1.785	1.807	1.652
15	9.758	1.809	1.592	1.566	1.584	1.613	1.643	1.677	1.706	1.732	1.756	1.777	1.626
16	9.854	1.768	1.568	1.543	1.559	1.590	1.620	1.649	1.679	1.705	1.729	1.752	1.602
17	9.703	1.734	1.549	1.527	1.543	1.570	1.600	1.627	1.654	1.682	1.705	1.728	1.581
18	9.047	1.703	1.523	1.508	1.525	1.550	1.580	1.604	1.633	1.657	1.680	1.699	1.562
19	8.500	1.670	1.508	1.494	1.509	1.536	1.563	1.589	1.611	1.638	1.659	1.677	1.545
20	8.227	1.648	1.492	1.478	1.497	1.518	1.544	1.574	1.598	1.618	1.643	1.656	1.529
21	8.063	1.627	1.479	1.465	1.484	1.503	1.531	1.557	1.580	1.601	1.620	1.641	1.514
22	7.297	1.607	1.467	1.456	1.467	1.495	1.518	1.543	1.563	1.586	1.606	1.625	1.501
23	6.422	1.586	1.453	1.442	1.457	1.480	1.506	1.528	1.552	1.574	1.590	1.610	1.488
24	6.094	1.575	1.446	1.432	1.449	1.471	1.491	1.515	1.541	1.558	1.573	1.592	1.477
25	5.656	1.552	1.434	1.426	1.438	1.459	1.482	1.503	1.527	1.548	1.563	1.578	1.466
26	5.109	1.540	1.422	1.413	1.428	1.449	1.473	1.494	1.514	1.535	1.550	1.564	1.456
27	4.445	1.529	1.412	1.405	1.420	1.438	1.463	1.483	1.504	1.522	1.540	1.557	1.446
28	3.953	1.516	1.406	1.397	1.411	1.432	1.453	1.476	1.496	1.515	1.532	1.547	1.438
29	3.748	1.504	1.398	1.391	1.402	1.425	1.444	1.465	1.484	1.503	1.521	1.535	1.429
30	3.516	1.494	1.392	1.382	1.397	1.414	1.437	1.457	1.476	1.493	1.508	1.521	1.421
31	3.270	1.480	1.384	1.377	1.389	1.408	1.427	1.446	1.47	1.484	1.500	1.521	1.414
32	3.254	1.479	1.380	1.368	1.377	1.401	1.428	1.447	1.469	1.467	1.490	1.510	1.406

TABLE IV
AS_{50} VALUES FOR VARIOUS SUBGROUP SIZE n AND $\beta = 13(1)24$

	Weibull distribution(1, β)												
n	(1,13)	(1,14)	(1,15)	(1,16)	(1,17)	(1,18)	(1,19)	(1,20)	(1,21)	(1,22)	(1,23)	(1,24)	N(0,1)
10	2.021	2.051	2.063	2.082	2.104	2.122	2.137	2.152	2.171	1.998	2.021	2.051	1.802
11	1.957	1.988	2.008	2.029	2.045	2.057	2.075	2.090	2.096	1.941	1.957	1.988	1.755
12	1.914	1.936	1.951	1.973	1.983	2.004	2.017	2.032	2.052	1.887	1.914	1.936	1.716
13	1.869	1.887	1.906	1.926	1.941	1.954	1.970	1.983	1.995	1.848	1.869	1.887	1.682
14	1.826	1.852	1.873	1.885	1.899	1.916	1.933	1.937	1.959	1.807	1.826	1.852	1.652
15	1.801	1.820	1.834	1.852	1.863	1.882	1.893	1.904	1.910	1.777	1.801	1.820	1.626
16	1.771	1.791	1.805	1.822	1.832	1.842	1.855	1.867	1.880	1.752	1.771	1.791	1.602
17	1.741	1.762	1.777	1.791	1.801	1.812	1.826	1.839	1.849	1.728	1.741	1.762	1.581
18	1.720	1.736	1.754	1.770	1.773	1.789	1.803	1.810	1.816	1.699	1.720	1.736	1.562
19	1.699	1.711	1.726	1.741	1.754	1.765	1.769	1.784	1.790	1.677	1.699	1.711	1.545
20	1.678	1.688	1.705	1.719	1.729	1.744	1.756	1.763	1.769	1.656	1.678	1.688	1.529
21	1.656	1.671	1.688	1.695	1.715	1.722	1.738	1.744	1.749	1.641	1.656	1.671	1.514
22	1.639	1.652	1.670	1.682	1.693	1.698	1.715	1.721	1.728	1.625	1.639	1.652	1.501
23	1.622	1.639	1.648	1.659	1.678	1.681	1.692	1.705	1.712	1.610	1.622	1.639	1.488
24	1.610	1.623	1.637	1.644	1.661	1.669	1.680	1.689	1.693	1.592	1.610	1.623	1.477
25	1.595	1.608	1.622	1.631	1.644	1.648	1.660	1.672	1.680	1.578	1.595	1.608	1.466
26	1.582	1.592	1.605	1.619	1.625	1.634	1.643	1.656	1.663	1.564	1.582	1.592	1.456
27	1.567	1.580	1.595	1.607	1.617	1.626	1.631	1.638	1.650	1.557	1.567	1.580	1.446
28	1.555	1.572	1.580	1.594	1.604	1.611	1.619	1.625	1.633	1.547	1.555	1.572	1.438
29	1.549	1.558	1.570	1.582	1.592	1.598	1.607	1.612	1.623	1.535	1.549	1.558	1.429
30	1.534	1.551	1.561	1.571	1.578	1.585	1.594	1.601	1.608	1.521	1.534	1.551	1.421
31	1.526	1.545	1.544	1.556	1.571	1.573	1.583	1.590	1.600	1.615	1.605	1.618	1.414
32	1.520	1.528	1.542	1.545	1.560	1.568	1.566	1.571	1.599	1.583	1.593	1.602	1.406

three quantiles ($F_{0.00135}$,$F_{0.5}$, and $F_{0.99865}$) under consideration, the corresponding C_{pu} and C_{pl} are defined as:

$$C_{pu} = \frac{USL - F_{0.5}}{F_{0.99865} - F_{0.5}}, \text{ and } C_{pl} = \frac{F_{0.5} - LSL}{F_{0.5} - F_{0.00135}}.$$

The index C_{pk} can be calculated as the minimum of C_{pu} and C_{pl}, namely:

$$\begin{aligned} C_{pk} &= \min\left\{C_{pu},\ C_{pl}\right\} \\ &= \min\left\{\frac{USL - F_{0.5}}{F_{0.99865} - F_{0.5}},\ \frac{F_{0.5} - LSL}{F_{0.5} - F_{0.00135}}\right\} \end{aligned}$$

Since standard deviation change ranging from 0 up to $AS_{50}\sigma$ may not be detected by control chart within short time and overestimation of the manufacturing yield may give incorrect feedback to the process control, the optimal approach is to simply accommodate any standard deviation change no greater than $AS_{50}\sigma$. When yield is calculated via the capability index, the AS_{50} must be incorporated into the capability assessment. Consequently, in this paper, we incorporate AS_{50} into the manufacturing yield assessment. We replace $F_{0.99865} - F_{0.5}$ and $F_{0.5} - F_{0.00135}$ with $AS_{50}(F_{0.99865} - F_{0.5})$ and $AS_{50}(F_{0.5} - F_{0.00135})$ in the new C_{pk} formula and present in the following:

$$\begin{aligned} C_{pk} &= \min\left\{\frac{F_{0.5} - LSL}{AS_{50}(F_{0.5} - F_{0.00135})}, \frac{USL - F_{0.5}}{AS_{50}(F_{0.99865} - F_{0.5})}\right\} \\ &= \min\left\{\frac{F_{0.5} - LSL}{AS_{50}\times F_{0.5} - AS_{50}\times F_{0.00135}},\right. \\ &\qquad \left.\frac{USL - F_{0.5}}{AS_{50}\times F_{0.99865} - AS_{50}\times F_{0.5}}\right\}. \end{aligned}$$

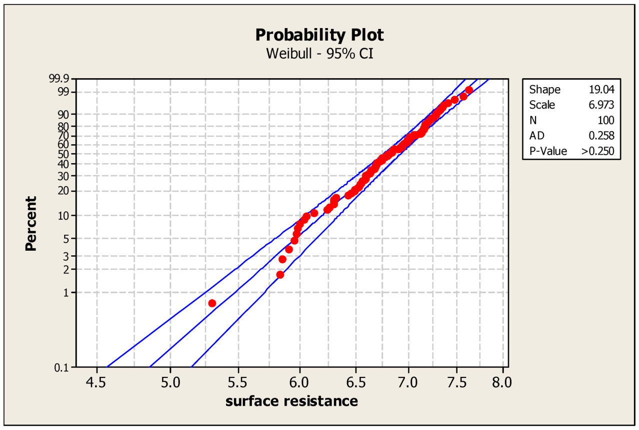


Fig. 5. Weibull probability plot of the data.

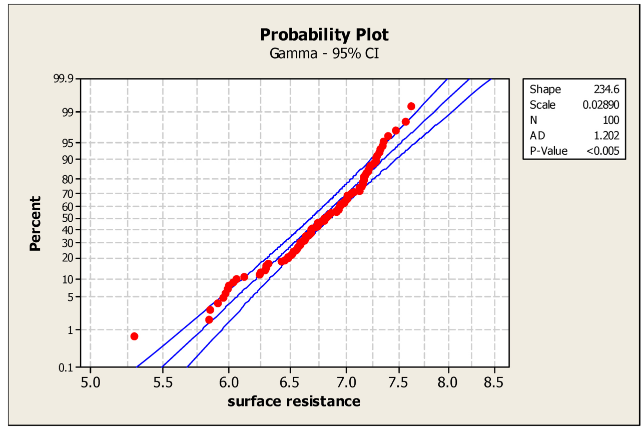


Fig. 6. Gamma probability plot of the data.

where $F_{0.00135}$, $F_{0.5}$, and $F_{0.99865}$ are the percentile points of the CDF of the Weibull -distributed in-cell touch panel manufacturing process. The methodologies used in this paper, is quite general. It can be applied to Gamma distributions, normal distributions, non-central chi-square distributions, and other distributions [6], [8], [12], [13].

IV. Manufacturing Yield Assessment for In-cell Touch Panel Manufacturing Process

To demonstrate the applicability of the proposed manufacturing yield assessment method, we consider a factory application taken from an in-cell touch panel manufacturing factory located in the Science-based Industrial Park at Hsinchu, Taiwan. In the case investigated, we consider the product type of TOD3205, which belongs to touch in display TID product series. Surface resistance is a critical specification in the in-cell touch panel manufacturing process. Higher or lower resistance degrades touch and display performance since touch sensing signal is synchronized with periodic display signal. Consequently, it is necessary to monitor the manufacturing stability of the electrode and control the surface resistance into the designated control limits.

In the section, we present a case to illustrate the application of the new capability index with variance change when the data of surface resistance collected from in-cell touch panel manufacturing processes are Weibull-distributed. In the case, specifications on surface resistance for the TOD3205 product are 5, 7.5, and 10 kΩ for LSL, $Target$, and USL, respectively. We collect 100 observations. Using the probability plot, the result indicates that the data approximates to be distributed as Weibull distribution since the p-value is greater than 0.250 (see Fig. 5). It is evident to conclude that the data collected from the in-cell touch panel shop floor is not Gamma-distributed by observing the probability plot in Fig. 6. In the Weibull distribution, values of the scale and shape parameters can be obtained as $\hat{\alpha} = 6.973$ and $\hat{\beta} = 19.04$, respectively.

As the case is a Weibull process, the three percentiles can be obtained in the following: $\hat{F}_{0.00135} = 5.2985$, $\hat{F}_{0.5} = 6.8134$, and $\hat{F}_{0.99865} = 7.6237$. The calculated value of the conventional $\hat{C}_{pk}$ is 1.1970. Thus, the corresponding manufacturing yield is 99.967% and the number of non-conformities in parts per million (NCPPM) is 329.412. The value of the conventional $\hat{C}_{pk}$ is not incorporated the accommodation of variance change and the yield would be overestimated.

As the value of $\hat{\beta}$ is 19.04, the value of AS_{50} is 1.756 when subgroup size $n = 20$ (see Table IV). The value of the modified process capability $\hat{C}_{pk}$ can be calculated as 0.6817. The value of the manufacturing yield is 95.916% and the number of non-conformities in parts per million (NCPPM) is 40845. It is noted that as the subgroup size is increased to 25, the value of AS_{50} is 1.660. The value of the modified process capability $\hat{C}_{pk}$ can be calculated as 0.7211. The value of the manufacturing yield is 96.948% as well as the number of non-conformities in parts per million is 30518. Using our method, the process capability and manufacturing yield can be obtained more accurately and the decisions are made more reliably.

V. Conclusion

In-cell touch panel manufacturing process performs the thinnest and lightest structure and has become new trend for fantastic user experience. The requirement of integration of in-cell touch panel manufacturing process would increase the difficulties of manufacturing. In in-cell touch panel manufacturing factories, surface resistance is a critical specification for uniform touch performance. Data of surface resistance is better described by Weibull- distrbuted. In addition, the typical yield measure approach ignored the fact that the variance of surface resistance may change. For the Weibull in-cell touch panel manufacturing processes, we applied the Monte-Carlo simulation method to determine the control limits of S^2 control chart and calculated the accommodations for various subgroup sizes (n) and Weibull parameter (β) with the designated detection power. We also showed the accommodation of the process capability index would not be affected by the scale parameter of a Weibull distribution. To avoid the overestimation of manufacturing yield, we presented a capability index method to calculate the manufacturing yield incorporating the factor of variance change. To demonstrate the applicability of the proposed method, we considered a real-world in-cell touch panel shop floor applications taken from the factory located in the Science-based Industrial Park at Hsinchu, Taiwan. The computational results showed that changing the sample subgroup sizes n, different values of capability indices would be obtained. Consequently, the corresponding manufacturing yields can be obtained more accurately. The results obtained could help the practitioners to make more reliable decisions on what actions need to take in controlling their in-cell touch panel manufacturing processes.

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