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Review

The effects of Tukey's control chart with asymmetrical control limits on monitoring of production processes

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Tukey's chart uses a single observation to monitor the process mean, and it is suitable for monitoring of destructive testing data. Tukey's chart adopts symmetrical control limits to monitor process and it is insensitive to signal mean shifts when the monitoring variable follows a skew distribution. This study proposes Tukey's chart with asymmetrical control limits (ACL-Tukey's chart) to monitor process mean. A statistical measurement performed with ACL-Tukey's chart, improves successfully, the ability in signaling shifts for monitoring of right-skew and left-skew populations. A real case of IC packaging is given to illustrate the practice procedure of ACL-Tukey's chart and indicates that ACL-Tukey's chart is suitable to monitor the industrial process.

Key words: Tukey's control chart, destructive testing, skew distribution, IC packaging process, statistical process control.

INTRODUCTION

Statistical process control (SPC) is the application of statistical methods to the monitoring and control of a process to ensure that it operates at its full potential to produce conforming product. The technology of control chart is a key tool in SPC. When an assignable cause occurs, the process will change. The control chart detects process changes and sends the operators to discover the assignable cause.

Currently, there are many types of control charts; when the control chart is applied to control process, the selection of an appropriate control charts must consider several factors such as sampling methods and monitoring procedures, etc. Many electronics manufacturers utilize a destructive testing approach to measure the process observations. After destructive testing and inspection, the testing sample is destroyed and cannot be sold on the market. Generally, for this kind of process monitoring, only one sample is taken to measure the observation so as to reduce cost. In this way, individual control charts are suitable to monitor the destructive testing data.

Tukey's chart uses a single observation to monitor the process mean (Alemi, 2004; Torng and Lee, 2008; Torng et al., 2009), thus making it suitable for monitoring destructive testing data. Tukey's chart has the advantage of easy and simple control limits setup, therefore, it can be adopted easily in real industry. Normal population is always a basic assumption of control charts, therefore, most control charts adopt symmetrical control limits to control the process. However, in real industry, process observation may violate this assumption and follows a skew distribution. Torng and Lee (2008) had presented that the performance of Tukey's chart is similar to Shewhart chart under both normality and non-normality.

The occurrence of an assignable cause may result in the positive or negative shift of the process mean. The performances of a control chart in detecting both positive and negative mean shifts are the same for symmetrical distributions, but it may be negative for skew distributions. If a control chart employs a sample of size larger than 30 to monitor process, the sample distribution will be approximately normal based on central limit theorem without respect to the symmetrical or skew population. However, when the sample size $n = 1$ is employed on control charts, the central limit theorem is not adopted, and then, the sample taken from the skew population cannot follow a symmetrical distribution. It causes the performances of the Tukey's chart to be different in the signaling of positive and negative shift.

The skew distribution can be divided to left-skew and right-skew distributions. Torng and Lee (2008) presented the performance of Tukey's chart in detecting positive shifts for right-skew populations but ignored to measure the performance in detecting negative shifts. This study measured the ability of Tukey's chart in detecting negative shifts for right-skew populations and discovered that the Tukey's chart is seriously insensitive to detect as further discussed. If the destructive testing data is the larger-the-better characteristic and follows a right-skew distribution, Tukey's chart can not detect quickly the negative shift of mean, and then, high defective rate may result. In addition, Torng and Lee (2008) also ignored to measure the performance for left-skew populations, and this performance should also be evaluated.

For controlling of skew population, a control chart with asymmetrical control limits can improve the ability in detecting shifts (Lin and Chou, 2007). This study will develop Tukey's chart with asymmetrical control limits to control right-skew and left-skew populations. A comparative study will be provided to show the performance of Tukey's chart with asymmetrical control limits in detecting both positive and negative shifts for controlling of skew population.

Wire bonding is a key process in IC packaging. For wire bonding process, the gold ball shear strength is an important quality characteristic and must be monitored. The inspection of gold ball shear strength adopts the destructive testing approach, therefore, this study will apply Tukey's chart to monitor gold ball shear strength testing value for performance evaluation. This case will be used to evaluate the feasibility that Tukey's chart with asymmetrical control limits applies on monitoring of skew population.

TUKEY'S CONTROL CHART

Alemi (2004) proposed the control procedure of Tukey's control chart which is a single observed value control chart and applies the principle of Box plot to set up its control limits. Torng and Lee (2008) constructed the control limits of Tukey's control chart under considering a known population. The control limits of Tukey's control chart are:

$$\begin{aligned} UCL &= F^{-1}(0.75) + k \times IQR \\ LCL &= F^{-1}(0.25) - k \times IQR \end{aligned} \qquad (1)$$

Where UCL and LCL are upper and lower control limits, respectively; $F^{-1}(\bullet)$ is an inverse of cumulative distribution function (cdf) of a known probability distribution; *IQR* is Inter-Quartile Range that is $F^{-1}(0.75) - F^{-1}(0.25)$; *k* is a control limit coefficient which determines the width of control limits. Tukey's control chart in Torng and Lee (2008) used symmetrical control limits to control process, therefore, this study calls it Tukey's chart with symmetrical control limits (SCL-Tukey's chart).

Assume the process mean and variance start μ_0 and σ^2, respectively, when process mean shifts, the new process mean becomes $\mu_1=\mu_0+\delta\sigma$, where δ is the shift size coefficient, $\delta=(\mu_1-\mu_0)/\sigma$. Let x be the sample observation, $P(\delta)$ be the probability that an observation falls outside control limits for a specific δ, $f(x)$ be the probability density function (pdf) of population, and then $P(\delta)$ is:

$$P(\delta) = 1 - \int_{LCL-\delta\sigma}^{UCL-\delta\sigma} f(x)\,dx \qquad (2)$$

Average run length (ARL) was widely used to measure the performance of control charts (Acosta-Mejia and Pignatiello, 2010; Dasa et al., 2009; Weiß, 2011; Knoth, 2005, 2006). ARL is defined as the expected value of the number of samples taken from the start of the process to the time when the chart indicates an out-of-control signal. The in-control ARL is used to measure the false alarm rate, and the out-of-control ARL represents the shift detecting ability of control chart. The ARL of Tukey's control chart for a specific δ is:

$$ARL(\delta) = 1/P(\delta) \qquad (3)$$

TUKEY'S CONTROL CHART WITH ASYMMETRICAL CONTROL LIMITS

To extend the design of Tukey's control chart earlier mentioned, this study proposes Tukey's control chart with asymmetrical control limits (ACL-Tukey's chart) to monitor skew population. Let k_U and k_L be the upper and lower control limit coefficients, and the upper and lower control limits of the Tukey's control chart can be rewritten thus:

$$\begin{aligned} UCL &= F^{-1}(0.75) + k_U \times IQR, \\ LCL &= F^{-1}(0.25) - k_L \times IQR. \end{aligned} \qquad (4)$$

The ARL and $P(\delta)$ of ACL-Tukey's chart can be obtained by the application of Equations (2) and (3). The occurrence of the shift process in real industry cannot be anticipated, it is very difficult to predict the shift sizes of process mean, therefore, it is very important that a control chart has good performance to detect the overall shift sizes rather than a specific mean shift. Average ARL (AARL) is very stable to be the performance index when the shift size is uncertain, and it was cited by Wu et al. (2004) and Ryu et al. (2010). AARL for shift range $[-\tau, \tau]$ is:

$$AARL = \int_{-\tau}^{\tau} w(\delta) ARL(\delta)\, d\delta \qquad (5)$$

Where $w(\delta)$ is the weight of $ARL(\delta)$. A small AARL value indicates the chart has good performance to signal the process variation. This study defines $w(\delta) = \delta^2$.

The control limit coefficients, k_U and k_L, must be determined before ACL-Tukey's chart is applied to process control. This study constructs a design model to optimize the control limit coefficients, k_U and k_L. The standard Shewhart's control charts were widely used to control process and their performance is as a criterion to measure the improving rate of performance of new control charts. The false alarm rate of a standard Shewhart's chart is about 370.4, therefore, an in-control ARL value of 370.4 is always used to be a common norm for comparing the performance (Balakrishnan et al., 2010; Torng and Lee, 2008). The constraint of this model limits in-control ARL to be 370.4, and its objective is to minimize the AARL. Therefore, this design model is:

$$\begin{aligned} &Min \quad AARL \\ &S.t. \quad ARL(\delta = 0) = 370.4 \\ &\qquad k_U, k_L \geq 0 \end{aligned} \tag{6}$$

Let k_L be equal k_U, the ACL-Tukey's chart becomes SCL-Tukey's chart.

Matlab optimization toolbox applies a nonlinear constrained optimization algorithm for solving of nonlinear models. De Magalhães et al. (2001), Mahadik and Shirke (2009), Lee (2010) and Torng and Lee (2009) had used Matlab optimization toolbox to determine the parameters of control charts. The performance indicators ARL and AARL will be coded with Matlab R2007a, and optimization toolbox is then applied to solve the control limit coefficients, k_U and k_L.

A COMPARATIVE STUDY

Selection of the skew population

The skew population can be divided into two types; left-skew and right-skew. Gamma distribution as a right-skew distribution, denoted by G (a,b), was always used to examine the performance of control charts. Torng and Lee (2008) presented the performance of SCL-Tukey's chart under several gamma distribution assumptions. Weibull distribution, denoted by W (β, η), can also become left-skew or right-skew type with the change of its shape parameter. Let observation x follow a weibull distribution, and its pdf is:

$$f(x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] \quad 0 \leq x \leq \infty, \beta > 0, \eta > 0 \tag{7}$$

Where η is a scale parameter; β is a shape parameter. If 0 < β < 3, weibull distribution is right-skew type; weibull distribution of 3 ≤ β ≤ 4 is approximate for the symmetrical distribution, and when β > 4, weibull distribution will become left-skew type. The expected value and variance of weibull distribution presented thus:

$$E(X) = \eta\Gamma(1 + 1/\beta), \tag{8}$$

$$V(X) = \eta^2\left\{\Gamma(1 + 2/\beta) + [\Gamma(1 + 1/\beta)]^2\right\}. \tag{9}$$

This study selects gamma and weibull distributions to examine the performance of control charts. The parameter choice of gamma distribution refers Torng and Lee (2008), and they are G (4,1), G (2,1) and G (1,1). For weibull distribution, this study chooses β = 10, 5, 3.5, 2, 0.8 and a fixed η = 1 to measure performance. Both W (10,1) and W (5,1) are left-skew distributions, W (3.5,1) is approximately a symmetrical distribution and W (2,1) and W (0.8,1) are right-skew distributions. Figure 1 shows the weibull distributions that were selected and their corresponding normal distributions that have the same mean and standard deviation.

COMPARISON AND DISCUSSION

A comparative study is conducted to evaluate the performance of both ACL-Tukey's and SCL-Tukey's charts. The false alarm rate of each chart is set to be equal, such that the comparison can be conducted in terms of the out-of-control ARL and AARL. The shifts of δ = -3, -2, -1.5, -1, -0.75, -0.5, -0.25, 0.25, 0.5, 0.75, 1, 1.5, 2 and 3 are chosen to obtain the out-of-control ARL and AARL values, so the τ of the design model is set at 3. The ARL and AARL calculations have been expressed in earlier discussion.

Let SCL mean the SCL-Tukey's chart and ACL indicate ACL-Tukey's chart. Table 1 provides the optimal design parameters of both SCL and ACL performances for each population. The in-control ARL values of all control charts are the same. For right-skew populations (for example, G (4,1), G (2,1), G (1,1), W (2,1) and W (0.8,1)), SCL and ACL have the same performance in signaling positive mean shifts, but SCL is seriously insensitive to signal negative mean shifts. ACL has better ability in detecting negative mean shifts than in detecting positive mean shifts. When the population distribution is closing to symmetry (for example, W (3.5, 1)), SCL and ACL have similar ability, and their performances in detecting both positive and negative mean shifts are the same. If populations are left-skew distributions (for example, W (10,1) and W (5,1)), the performance of SCL is slightly better than the performance of ACL in signaling negative mean shifts, but the ability of ACL is conspicuously better than the ability of SCL in detecting positive mean shifts. To

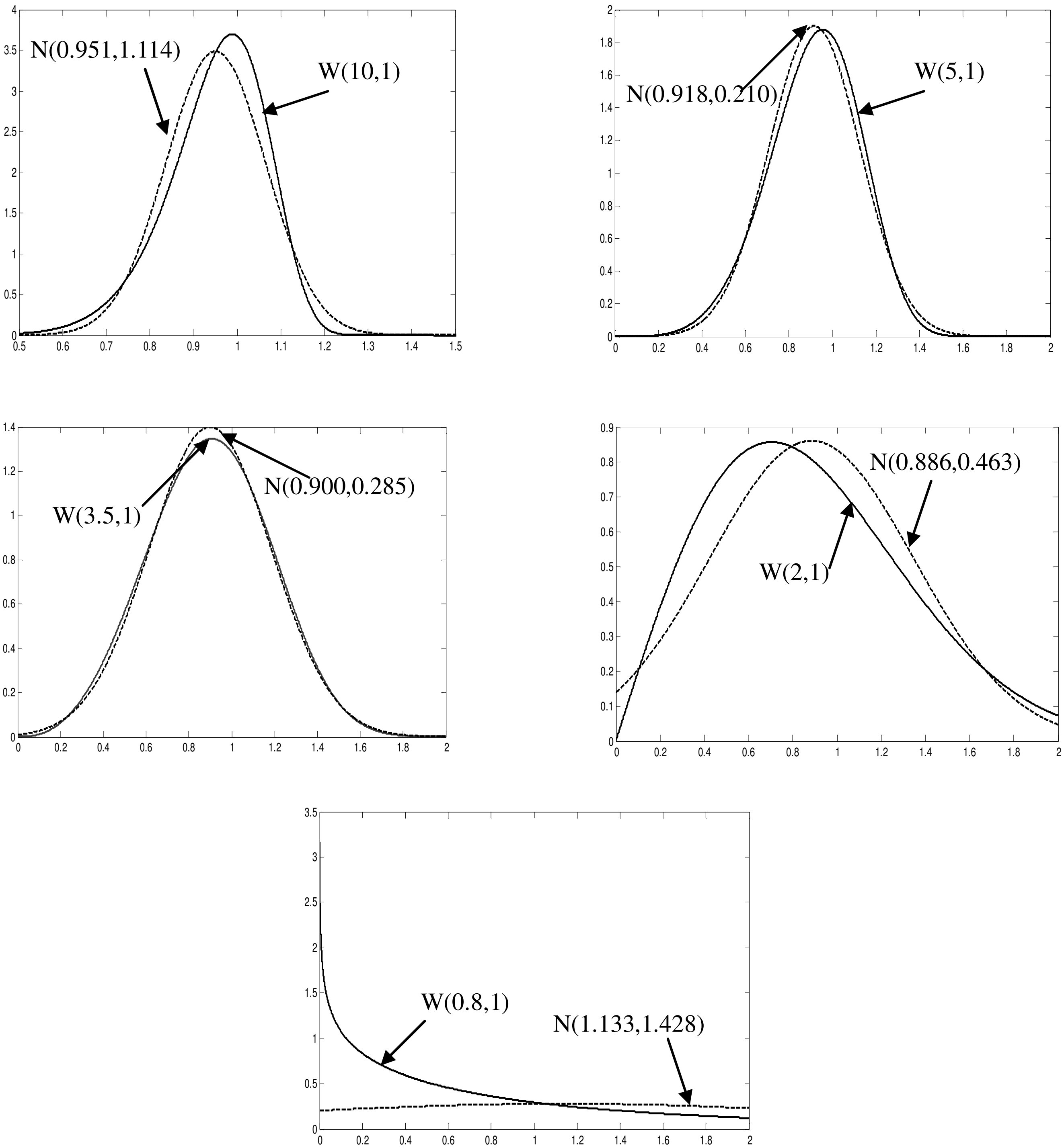

Figure 1. The probability density function for various weibull and normal distributions.

compare the AARL values of both charts, the perfor -mances of ACL are better than the performances of SCL when the population is a left-skew distribution. ACL and SCL have the same performance and control chart design under normality. In addition, AARL values of W (10,1) and W (5,1) are smaller than that of N (0,1). Therefore, ACL-Tukey in monitoring of left-skew populations has better performance than in monitoring of normal population.

In summary, ACL is more suitable to control skew population than SCL. If the process observation follows a skew distribution, ACL is suggested to monitor this

Table 1. Values of the ARL and AARL of Tukey's control charts.

	G (4,1)		G (2,1)		G (1,1)		W (10,1)		W (5,1)		W (3.5,1)		W (2,1)		W (0.8,1)		N (0,1)	
Charts	SCL	ACL	SCL	ACL	SCL	ACL	SCL	ACL	SCL	ACL	SCL	ACL	SCL	ACL	SCL	ACL	SCL	ACL
k_U	2.594	2.667	3.138	3.138	4.122	4.122	2.190	1.239	1.654	1.353	1.466	1.468	1.957	2.121	5.968	5.976	1.7238	1.7238
k_L	2.594	0.859	3.138	0.555	4.122	0.262	2.190	2.298	1.654	1.787	1.466	1.462	1.957	0.785	5.968	0.163	1.7238	1.7238
UCL	11.787	11.973	8.126	8.126	5.915	5.915	1.362	1.219	1.544	1.457	1.680	1.681	2.432	2.537	9.224	9.234	3.0000	3.0000
LCL	-4.142	0.325	-4.472	0.000	-4.241	0.000	0.554	0.537	0.303	0.265	0.118	0.119	-0.718	0.033	-7.509	0.000	-3.000	-3.000
δ									ARL									
-3.00	8.46	1.14	17595	1.08	7441.1	1.05	3.49	4.09	1.97	2.28	1.68	1.67	2.75	1.15	3058.3	1.04	2.00	2.00
-2.00	9006.1	1.59	4783.7	1.29	2737.4	1.16	12.12	14.84	5.56	7.13	4.23	4.21	23.55	1.66	1539.6	1.11	6.30	6.30
-1.50	3977.6	2.35	2507.0	1.60	1660.3	1.29	25.33	31.66	11.57	15.72	8.87	8.80	17629	2.43	1085.9	1.19	14.96	14.96
-1.00	1777.5	4.85	1319.0	2.42	1007.0	1.58	56.98	72.80	28.60	41.86	24.60	24.32	4369.6	4.58	762.44	1.36	43.88	43.88
-0.75	1194.1	8.81	958.38	3.48	784.29	1.89	88.00	113.76	48.73	74.77	47.93	47.26	2264.7	7.40	637.76	1.53	81.19	81.19
-0.50	805.05	21.39	697.16	6.26	610.80	2.53	138.81	181.41	88.88	143.17	108.08	106.22	1205.7	14.67	532.80	1.87	155.16	155.16
-0.25	544.82	85.66	507.80	19.39	475.69	4.48	223.97	288.36	175.76	277.74	266.01	261.47	659.39	43.83	444.54	2.80	281.03	281.03
0.00	370.22	370.40	370.38	370.40	370.47	370.40	370.40	370.40	370.40	370.40	370.40	370.40	370.40	370.40	370.40	370.40	370.40	370.40
0.25	252.69	291.28	270.56	270.58	288.52	288.52	629.38	227.43	623.05	214.95	196.45	198.29	213.72	351.25	308.19	309.87	281.03	281.03
0.50	173.29	199.40	197.96	197.97	224.70	224.70	1101.3	84.66	417.26	90.77	90.99	91.80	126.67	203.19	256.04	257.45	155.16	155.16
0.75	119.45	137.18	145.10	145.11	175.00	175.00	1955.5	32.84	165.70	40.63	45.67	46.02	77.12	120.73	212.39	213.56	81.19	81.19
1.00	82.80	94.89	106.56	106.57	136.29	136.29	2694.1	15.03	68.05	20.36	24.80	24.97	48.23	73.69	175.89	176.87	43.88	43.88
1.50	40.55	46.24	57.85	57.85	82.66	82.66	302.48	4.92	16.43	6.96	9.05	9.10	20.44	29.75	119.99	120.67	14.96	14.96
2.00	20.45	23.18	31.72	31.73	50.14	50.14	33.19	2.48	5.99	3.31	4.24	4.26	9.65	13.37	81.22	81.69	6.30	6.30
3.00	5.84	6.51	9.95	9.95	18.44	18.44	3.35	1.31	1.89	1.47	1.67	1.67	2.96	3.73	36.18	36.41	2.00	2.00
									AARL									
	613.73	228.56	614.55	286.69	694.07	428.15	1844.0	78.32	146.12	75.32	75.21	75.20	953.20	156.00	885.34	674.91	116.91	116.91

process.

APPLIED ACL-TUKEY'S CHART TO MONITOR WIRE BONDING PROCESS OF IC PACKAGING

Wire bonding is a key process in IC packaging and is the most common method for electrically connecting the aluminum bonding pads on a microchip surface to the package inner lead terminals on the lead-frame. Thermosonic ball bonding technology is applied to the wire bonding process. The thermosonic ball bonding uses a capillary tip made of tungsten carbide or ceramic material which feeds a fine diameter Au wire vertically through a hole in its center. The protruding wire is heated by a small flame or capacitor discharge spark, causing the wire to melt and form a ball at the tip. During bonding, the ultrasonic energy and the pressure cause a metallurgical bond to form between the Au wire and the Al pad. Upon completion of the ball bond, the bonding mechanism moves to the substrate inner lead pad and forms a thermo compression wedge bond. Up to this phase, the wire is broken and the tool continues to the next die bonding pad.

During the wire bonding process, the gold ball

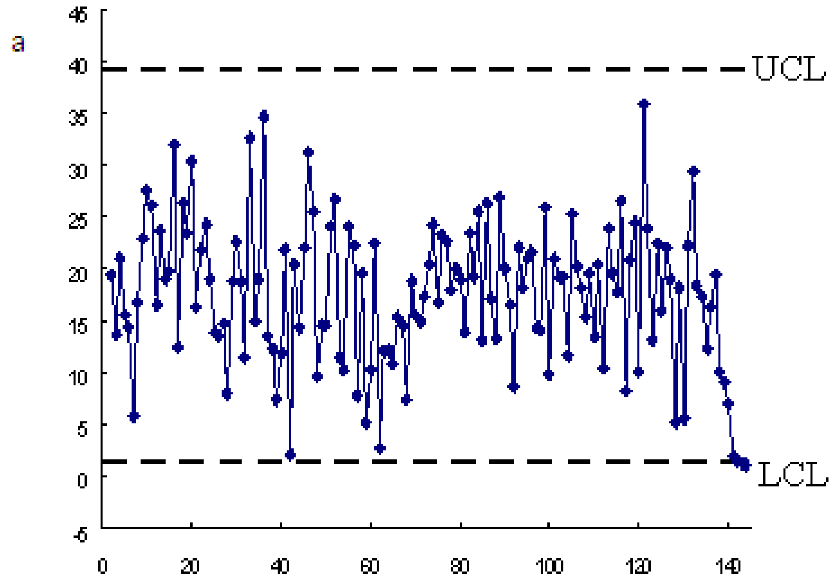

Figure 2a. Tukey's charts for monitoring of a wire bonding process, (ACL- Tukey's chart)

Shear strength is an important quality characteristic and must be monitored. The destructive testing approach is utilized to measure the ball shear strength. Since the ball shear strength variance of the same IC is very small, previous sampling approaches sampled one IC and randomly selected one ball from it to perform testing. As a consequence, only single shear strength can be obtained during each testing for the monitoring. The gold ball shear strength is the larger-the-better characteristic. When the gold ball shear strength mean becomes small, the control chart must signal quickly this variation for eliminating the assignable cause. As a result of signaling quickly, the mean shifts ACL-Tukey's chart is selected to control the gold ball shear strength mean.

Since historical data obtains 100 testing values of ball shear under in-control process, these testing values are verified following weibull distribution with β = 2.82 and η = 20.55 through application of the Kolmogoroc-Smirnov test (P-value = 0.477). The mean and standard deviation of these testing values are 18.304(g) and 7.032, respectively, and the $F^{-1}(0.75)$, $F^{-1}(0.25)$ and *IQR* are 13.2110, 23.0736 and 9.8626, respectively. Let $f(x)$ be the pdf of weibull distribution with β = 2.82 and η = 20.55, compute the ARL and AARL functions, and take them to the design model. Let k_U and k_L be the decision variables to design ACL-Tukey's chart, the optimal k_U and k_L are 1.589 and 1.243, respectively, and then the *UCL* and *LCL* are 38.7486 and 0.9518, respectively. A similar approach can obtain the optimal k value of SCL-Tukey's chart, the optimal k is 1.5739, and then *UCL* and *LCL* of SCL-Tukey's chart are 38.5961 and -2.3115, respectively.

Figures 2a and b shows the monitoring of wire bonding processes during 144 periods. The ACL-Tukey's chart signals a shift at 143 rd sampling, but SCL-Tukey's chart does not signal any variation during 144 periods. An investigation of the operation procedure knows the occurrence cause of this variation is due to use of a fault machine parameter between 137th to 138th sampling. The gold ball shear strength mean reduces to 7.267(g) from 18.304(g), and the shift size δ is about -1.57. This practical case shows ACL-Tukey's chart has better ability in signaling the negative shift than SCL-Tukey's chart for the right-skew population and ACL-Tukey's chart is more suitable than SCL-Tukey's chart in monitoring the real industrial process.

CONCLUSIONS

This study proposes Tukey's chart with asymmetrical control limits (ACL-Tukey's chart) to monitor skew population. A comparative study of the statistical measurement and a real case of IC packaging are given respectively to show the performance of ACL-Tukey's chart in monitoring of the skew population from the theoretical and practical viewpoints.

In this comparative study, ACL-Tukey's chart in signaling negative mean shift is more sensitive than Tukey's chart with symmetrical control limits (SCL-Tukey's chart), but ACL-Tukey's chart and SCL- Tukey's chart have similar performance in signaling positive shift for monitoring of right-skew population. If population follows a left-skew distribution, it can obtain the contrary result to the monitoring of right-skew population in the performance of signaling positive and negative shifts. A statistical design model can provide the optimal parameters of ACL-Tukey's chart for monitoring of skew

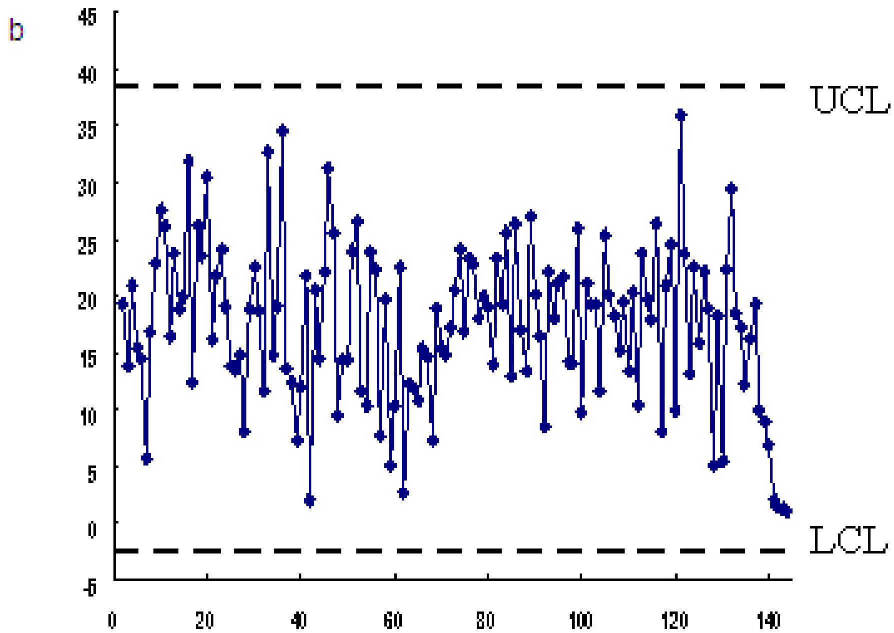

Figure 2b. Tukey's charts for monitoring of a wire bonding process, (SCL- Tukey's chart),

populations. A case of IC packaging provides a procedure to carry out ACL-Tukey's chart monitoring the industrial process. This case also verifies the good ability of ACL-Tukey's chart in signaling shifts and SCL-Tukey's chart is insensitive to signal shifts for monitoring the skew population. If the process observation follows a skew distribution, ACL-Tukey's chart is suggested to monitor this process.

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