Research on quality warning of PZT sintering process based on SPC

Can Wang*, Zeyu Wang and Fei He
School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, China
*Corresponding author: wangcan@njust.edu.cn

Abstract. In the small-batch production mode of multiple varieties of piezoelectric ceramics, according to the special requirements of batch sintering of the same batch of products in the sintering process, as well as the lack of quality sample data, quality status monitoring and inaccurate early warning, a combined process quality monitoring method of general control chart and CUSUM control chart was proposed. The method can effectively identify the slight deviation of quality and realize the early warning of process quality. The feasibility of this method is verified in this paper.

Keywords: Piezoelectric ceramics, SPC, Sintering process, The quality of early warning.

1. Introduction
With more and more extensive application, the production mode of piezoelectric ceramics has gradually changed from mass production to multi-variety and small-batch production, and the quality requirements are stricter. In the multi-variety and small-batch production mode, the production category changes quickly and the quality sample data is less. Once quality problems occur, the whole batch of products may be scrapped. Therefore, it has become an urgent problem in the production of piezoelectric ceramics to effectively identify and timely warn the small deviation in sintering process. Mihalcin [1] et al. proposed a SPC method based on control chart for monitoring multiple quality characteristics of the production process. Based on the statistical process control method, Wan [2] et al. established a multivariate process control chart for the relevant data of multiple stages in the production process. However, in the mode of multi-variety and small batch, it is difficult to detect the small mass deviation due to the lack of quality sample data. Haq [3-4] et al. proposed improved EWMA control chart and CUSUM control chart, which effectively improved the recognition accuracy of mean change in normal distribution process. Ali [5] et al. proposed a new CUSUM control chart of weighted moving average statistics, which further improved the sensitivity of process monitoring.

However, the existing SPC theory and quality warning method are mainly focused on the continuous production mode of multiple varieties and small batches, while for the special mode of simultaneous production of multiple specifications under the same process, there is no relevant theory and method to analyze it at present. Therefore, in view of the actual production situation of the sintering process of piezoelectric ceramics and the production mode of multi-varieties and small batches, a joint control
A method of general control chart and CUSUM control chart was proposed in this paper to realize the early warning of abnormal sintering process.

2. SPC method for piezoelectric ceramics sintering process

In SPC theory, general control chart is set for mass production and its application requires a lot of data analysis. However, the production of piezoceramics is a multi-variety and small-batch production mode, which restricts the application of the general control chart to a certain extent. Therefore, based on the characteristics of sintering with batch number of the same batch of products in the sintering process, this paper took products with different batch Numbers as samples and transformed the quality control problem of multi-variety small-batch production process into the quality control problem of large-batch production process through data conversion.

In addition, although the general control chart has good detection performance when the sample mean is greatly shifted, when the mean deviation degree is small, the detection output is weak and the reaction to the small deviation in the process is not sensitive. Compared to the general control chart, the CUSUM control chart contains all the information of the sample value sequence, which can effectively identify small offsets in the process. In consideration of the shortage of quality data in multi-varieties and small batches and the insensitivity of general control chart to small deviations, a joint control method of $\bar{x} - s$ control chart and CUSUM control chart was proposed in this paper, so as to effectively control the abnormal state of quality in sintering process.

3. Processing of sintering quality data

The test data of P41($\varnothing 20 \times 1$mm) piezoelectric ceramic wafer produced by a piezoelectric ceramics factory was selected as the test variable. The sintering density of the ceramic billet after the sintering process is taken as the basis for testing the sintering quality. Since the statistical quality characteristics between samples, total standard deviation $\sigma$ and sample standard deviation $S$ are similar, they can be combined into one sample for analysis, and therefore must be converted into uniformly distributed data for analysis. Since the data of production samples are approximately normally distributed, the basic data are converted into standard normal distribution $N(0, 1)$. Because the target value and tolerance zone of the density index of piezoelectric ceramics are known, the tolerance coefficient method is adopted for conversion. The conversion formula is as follows:

$$X = \frac{Z - M}{T}$$

Where, $X$ is the converted value of sample quality data; $Z$ is the actual measured value of the sample data; $M$ is the target value of sample quality data; $T$ is the product tolerance zone.

Through standard transformation, the distribution of sample variables of the sintering density of piezoelectric ceramics is transformed into a normal distribution, as shown in Table 1. The transformed standard data is then plotted in the control chart.
Table 1. Standard conversion value of sintering density of piezoelectric ceramics

| Batch number | Standard conversion value | Mean   | Standard deviation |
|--------------|---------------------------|--------|-------------------|
| 1            | 0.031 -0.062 0.323 0.017 0.026 | 0.122  | 0.188             |
|              | 0.280 0.163 -0.196 0.385 0.249 |       |                   |
| 2            | -0.059 -0.029 -0.262 -0.194 -0.165 | -0.053 | 0.184             |
|              | 0.171 0.140 -0.149 -0.236 0.254 |       |                   |
| 3            | 0.215 -0.232 0.107 -0.071 -0.054 | 0.034  | 0.150             |
|              | 0.209 -0.030 -0.070 0.197 0.069 |       |                   |
| …            | … … … … … | … … | … … |
| 18           | -0.048 -0.104 0.063 0.261 -0.196 | 0.062  | 0.174             |
|              | 0.036 0.080 0.214 -0.048 0.360 |       |                   |
| 19           | 0.094 0.214 0.079 0.162 0.165 | 0.103  | 0.062             |
|              | 0.038 0.078 0.065 0.111 0.017 |       |                   |
| 20           | 0.101 0.112 0.127 0.033 0.106 | 0.126  | 0.042             |
|              | 0.168 0.178 0.145 0.131 0.163 |       |                   |

4. $\bar{x} - s$ control chart

The types of general control chart mainly include measurement value control chart and counting value control chart. This paper uses the mean-standard deviation control chart in the measurement value control chart. The $\bar{x}$ chart is used to observe the distribution changes of sample mean and the central deviation of the reaction process. The $s$ chart is used to observe the change of process standard deviation. In the mean-standard deviation control chart, the vertical axis represents the output value of the production quality characteristics, and the horizontal axis represents the time. At the same time, the figure also includes the center line and the upper and lower control lines.

It is assumed that the production process is under control. When the point corresponding to the quality output value of the production process falls outside the control line, the process is out of control. Therefore, it is necessary to analyze the process and find out the abnormal factors.

In the $\bar{x} - s$ control chart for the collected quality, the control line of the mean control chart is:

$$\bar{X} = \frac{\bar{X}_1 + \bar{X}_2 + \ldots + \bar{X}_k}{k}$$

$$s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (X_i - \bar{X}_j)^2$$

$$\bar{s} = \frac{s_1 + s_2 + \ldots + s_n}{n}$$

$$\begin{align*}
UCL_{\bar{X}} &= \bar{X} + A_3 \bar{s} \\
CL_{\bar{X}} &= \bar{X} \\
LCL_{\bar{X}} &= \bar{X} - A_3 \bar{s}
\end{align*}$$

Where, $\bar{X}$ is the population mean of each group of sample means; $\bar{X}_k$ is the mean value of the sample quality data collected in group k; $S$ is the variance of the sample in group j; n is the sample size of group j; $\bar{X}_j$ is the corresponding mean of the samples of group j; $X_i$ is the ith sample quality data of group j; $A_3$ is a constant related to n; $\bar{s}$ is the mean of $s$; $UCL_{\bar{X}}$, $CL_{\bar{X}}$, $LCL_{\bar{X}}$ are the upper, middle and lower control lines of the mean value control chart respectively.

The control line of the standard deviation control chart is:
Where, \( UCL_s \), \( CL_s \), \( LCL_s \) is the upper, middle and lower control line of the range control chart; \( B_3 \), \( B_4 \) are constants associated with \( n \).

As the products of the same batch were sent into the furnace for sintering in 10 batches, the subgroup capacity \( n=10 \) was set according to the batch number, and \( A_3=0.975 \), \( B_3=0.284 \), \( B_4=1.716 \) were obtained by inquiring the coefficient table of the control chart. The converted standard data is then plotted and the \( \bar{x} - s \) control chart is shown in Figure 1.

![Figure 1. \( \bar{x} - s \) control chart of sintering density of piezoelectric ceramics](image)

As can be seen from the established \( \bar{x} - s \) control chart, the actual sample points were randomly arranged. A cause check was performed on the control chart and no points were found to be above the control line, all points were increasing or decreasing at 6 consecutive points, and 2 points in 3 consecutive points were greater than 2 standard differences, etc. The test results show that the sintering quality is qualified, and there is no trend of increasing or decreasing quality, which indicates that there is no abnormal state in the process, which is consistent with the actual production.

5. CUSUM control chart

In the CUSUM control chart, the quantitative calculation is the cumulative sum of the difference between the sample value and the target value, which contains all the information of the sample value sequence. The process of difference determination is to detect this statistic with a limit. Suppose the sample size collected is \( n \), \( \bar{X}_K \) is the mean value of the sample quality data collected in group \( K \). If \( \mu \) represents the target value of the process mean, then CUSUM statistic is \( C_k = \sum_{k=1}^{k} (\bar{X}_k - \mu_0) \), in which \( C_k \) is the cumulative sum up to the \( k \)th sample. When the process is stable, statistic \( C_k \) is a variable that fluctuates randomly near 0. If there is deviation in the process, the deviation will be accumulated into statistic \( C_k \) and reflected in the CUSUM control chart, that is, the curve has an upward or downward trend. When \( C_k \) exceeds the control limit, it will be judged that the process is out of control.
Through the collected sample quality data, a CUSUM control chart is established, and its calculation formula is as follows:

\[ C_H(j) = \max [0, \bar{X}_j - (\bar{X} + Q) + C_H(j - 1)] \]  
(7)

\[ C_L(j) = \max [0, (\bar{X} + Q) - \bar{X}_j + C_L(j - 1)] \]  
(8)

\[ C_H(0) = C_L(0) = 0 \]  
(9)

Where, \( C_H(0), C_L(0) \) is the upper unilateral accumulation and the lower unilateral accumulation respectively; \( Q \) is the allowance for deviation.

If the mean deviation from \( \bar{X}_j \) to \( \bar{X}_{j+1} \) is alarming, then \( Q = t \sigma \). The upper and lower limit judgment value in CUSUM control chart is \( H \). If the upper and lower side statistics in the chart exceed \( H \), it will be judged as process out of control. Usually, the effective parameters of CUSUM control chart are \( H=5\sigma \), \( t=0.5 \).

Then, the CUSUM control chart is used to identify whether there is a slight deviation in the sintering process, and the converted standard data is drawn for the control chart. The CUSUM control chart is shown in Figure 2.

**Figure 2.** CUSUM control chart of sintering density of piezoelectric ceramics

As can be seen from Figure 2, sample points are randomly arranged in the control chart, and no continuous points are parallel to both sides of the center line, indicating that the control line of the control chart is reasonably selected. The figures shows that the accumulative curve sample point drops continuously from point 3 to point 5, but the accumulative line is still within the control line, but it drops significantly from point 14 to 20, and the accumulative curve has gone beyond the control line. It can be seen that the sample quality of batch no. 14 to batch No. 20 fluctuates greatly, and the sintering process shows an abnormal trend, and the process is out of control.

In combination with figure 1 and figure 2, it can be found that, although the actual sample points in the \( \bar{X} - s \) control chart are within the quality control limits, the control chart shows that no quality abnormality has occurred and the sample quality is still within the tolerance range. However, according to the control chart of CUSUM, it can be determined that the quality state will continue to drift downward and eventually exceed the control line. Thus, it can be concluded that the sintering process has gradually become out of control. Therefore, it is necessary to immediately analyze the quality
influence related to sintering process and timely adjust and solve this problem. It can be seen that the application of joint SPC control chart can monitor the quality status of key processes and effectively warn the quality anomalies of processes.

6. Conclusion
Based on piezoelectric ceramic enterprise many varieties of small batch production mode, combined with the actual production of the sintering process, put forward the $\bar{x} - s$ control chart and CUSUM control chart of statistical method, the sintering process is effective to identify tiny shift of quality characteristics, timely warning of out of control of sintering process, quality monitoring and control for piezoelectric ceramic manufacturing enterprise provides an effective and feasible method.

Acknowledgements
This paper was financially supported by the Jiangsu Province military and civilian integration development guidance fund project. Project number: 1171061540.

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