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Applied Computer Systems

ISSN 2255-8691 (online)
ISSN 2255-8683 (print)
December 2018, vol. 23, no. 2, pp. 128–134
doi: 10.2478/acss-2018-0016
https://content.sciendo.com

Models of Printed Circuit Boards Conductive Pattern Defects

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Abstract **– A number of PCB defects, though having passed successfully the defect identification procedure, can potentially grow into critical defects under the influence of various external and (or) internal influences. The complex nature of the development of defects leading to PCB failures demands developing and updating the data measuring systems not only for detection but also for the prediction of future development of PCB defects considering the external influences. To solve this problem, it is necessary to analyse the models of defect development, which will allow predicting the defect growth and working out the mathematical models for their studies.**

The study uses the methods of system analysis, theory of mathematical and imitation modelling, analysis of technological systems. The article presents four models for determining the theoretical stress concentration factor for several types of common defects, considering the strength loss of PCB elements. For each model the evaluation of parameters determining its quality is also given. The formulas are given that link the geometry of defects and the stress concentration factor, corresponding to four types of defects. These formulas are necessary for determining the number of cycles and time to failure, fatigue strength coefficient.

The chosen models for determining the values of the stress concentration factor can be used as a database for identifying PCB defects. The proposed models are used for software implementation of the optical image inspection systems.

Keywords **– Conductive paths, mathematical model, mechanical stresses, PCB defect, printed circuit board.**

I. Introduction

Current electronic devices are manufactured on the basis of a printed board assembly of multi-layered structure that consists of dielectric base and the conductive pattern. Electronic devices are used in different working environments, depending on the sphere of their application, but all of them are required to conform with strict reliability criteria. Aerospace and defense industries set the highest reliability criteria as the electronic devices in these industries are to be used for a long time and in harsh environments.

It is known that in 30 %–40 % of failures, the causes are PCB defects, the reasons for which are the production faults.

To identify and localize these defects efficiently, the traditional methods of data measuring systems are used that allow for active control and diagnostics of the product at all technological stages of manufacture.

The aim of all data measuring systems for monitoring the electronic devices is to identify the critical defects leading to failures. At present, the production of printed circuit assemblies employs optical, electric, X-ray, thermal and other methods of control. The control procedures have to be conducted in minimum time with minimum efforts. The optical method of control satisfies these demands. It can be used both for monitoring the PCBs and PCB assemblies. The reliability of electronic devices is largely determined by the quality of PCBs, and the major element of these is the conductive pattern.

When the conductive pattern of PCBs are monitored visually during optical control, the chance of missing a certain defect is high due to the subjectiveness of the method. That is why, the human factor risk has to be reduced by means of automated analysis of defects.

A number of PCB defects, though having passed successfully the defect identification procedure, can potentially grow into critical defects under the influence of various external and (or) internal influences. The complex nature of the development of defects leading to PCB failures demands developing and updating the data measuring systems not only for detection but also for the prediction of future development of PCB defects considering the external influences.

To solve this problem, it is necessary to analyse the models of defect development, which will allow predicting the defect growth and working out the mathematical models for their studies.

II. Stress Concentration Model

There are conditions lowering the element strength limit: stress concentration, surface quality, size, etc. Let us single out the stress concentration as the leading determinant that influences stress resistance and operating lifespan. Multiple experiments prove that the regions where the element form changes sharply (technological defects – pits, tear-outs, cracks) have the highest stresses. Thus, if tensile stress is applied to the conductor with broken out sections, the law of equal stress distribution changes in the areas close to these sections. The stress-strain state arises, with the stress peak next to the edges of the broken out sections [1]–[4].

Let us take an element with a circular hole (pit) as an example (Fig. 1).

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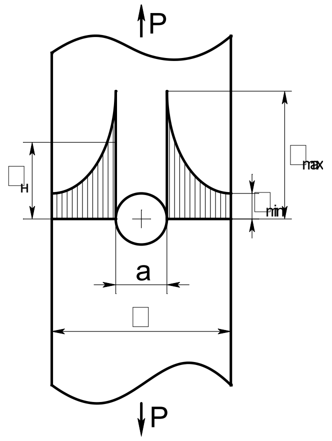

Fig. 1. The element weakened by the presence of a circular hole.

The growth of local stresses in the element weakened by the defect is measured by a stress concentration factor:

$$K_t = \frac{\sigma_{\text{max}}}{\sigma_{\text{nom}}}, \tag{1}$$

where σ_{max} is the biggest local stress; σ_{nom} is the nominal stress calculated without a stress concentration parameter.

Depending on the material and type of stress, the stress concentration produces different influence on the element strength. That is why the effective stress concentration factor, the value of which with cycle changes of stress (with $R = -1$) is determined according to the formula:

$$K = \frac{\sigma_{-1}}{\sigma'_{-1}}, \tag{2}$$

where σ_{-1} is the fatigue (endurance) limit for the element, and σ'_{-1} is the fatigue (endurance) limit calculated using nominal stresses for the element with stress concentration.

The value of effective stress concentration factor can be obtained experimentally. However, at present there is a lot of data that allows establishing the connection between the theoretical and effective stress concentration factors in the form of:

$$K = 1 + q(K_t - 1), \tag{3}$$

where q is the sensitivity coefficient of materials to local stresses. Its value is primarily determined by material properties. In some degree, the geometry of the element has an influence on q change.

To determine the sensitivity coefficient of material, the method described in [2], [5]–[7] can be applied. In some cases, due to the lack of data for the sensitivity coefficient of the material, for new types of foils of PCBs in particular, the theoretical concentration factor K_t can be used. It should be noted that without considering the material sensitivity coefficient ($q = 1$), the error goes to strength margin: $K=K_t$.

Values of theoretical stress concentration factor K_t are not dependant on the level of nominal stresses and physical properties of the material, but are determined by the geometry of the element, type of load and relative size of stress concentration areas.

Values of theoretical stress concentration factor for some types of defects are determined with the help of analytical formulas or graphs showing its dependency from the geometrical parameters of the element and the defect itself. These dependencies are determined experimentally, measuring photoelasticity, interferometry, strain, moiré fringe, etc. and are given in reference books on stress concentration, norms, engineering requirements for various types of structural elements.

Due to the influence of stress concentration factor, the curves corresponding to endurance limit (Fig. 2 and Fig. 3 – thin lines) change their position (Fig. 2 and Fig. 3 – thicker lines); hence, the number of cycles and time to failure, fatigue strength become lower.

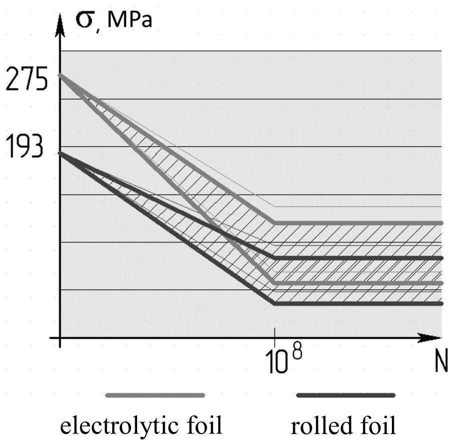

Fig. 2. Stress-number curve.

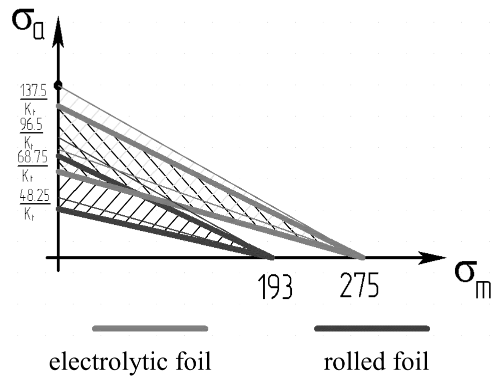

Fig. 3. Limiting amplitude diagram.

In this way, the fatigue strength coefficient with stress concentration is calculated using the formulas:

with symmetrical cycle:

$$n = \frac{\sigma_{-1}}{K\sigma_{\text{max}}}, \tag{4}$$

with asymmetrical cycles:

$$n = \frac{\sigma_{-1}}{K\sigma_{\text{a}} - \psi\sigma_{\text{m}}}. \tag{5}$$

Study [4], [8] generalizes the data on theoretical stress concentration factors for different types of defects. These data served as a basis for comparing different types of technological defects and models, in the form of empirical formulas or correlations, found by approximating data of experimental graphs.

To choose the type of correlation, with the closest approximation to the data in the form of experimental graphs, the dependency is approximated using the following models [7], [9]–[11]:

- linear;
- quadratic function;
- cubic function;
- power function;
- exponential function;
- logarithmic;
- hyperbolic approximation;
- exponential approximation.

When assessing the selected models for the final selection, we used the following criteria of model quality:

- correlation coefficient;
- determination coefficient;
- mean approximation error.

Correlation coefficient is the value that shows the strength of relations between the parameters. It can vary within the range between +1 and –1. If the modulus close to 1 means the presence of strong connection, and in case it is close to 0, then the connection is absent or is significantly not linear one.

$$r = \frac{\sum (K_t - \overline{K_t})(\hat{K}_t - \overline{\hat{K}_t})}{\sqrt{\sum (K_t - \overline{K_t})^2 \sum (\hat{K}_t - \overline{\hat{K}_t})^2}}, \quad (6)$$

where K_t are the values of theoretical stress concentration factor, experimental curves data are used:

$\overline{K_t}$ is the mean value of the theoretical stress concentration factor, experimental curve data are used;

$\hat{K}_t$ are the values of theoretical stress concentration factor based on selected correlations;

$\overline{\hat{K}_t}$ is the mean value of the theoretical stress concentration factor based on selected correlations.

Determination coefficient is the main parameter that shows the quality degree of the regression model that described the relations between the dependent and independent values of the model. The closer R^2 is to 1, the higher is the model quality. With R^2 equal, the regression line corresponds to all observations.

$$R^2 = 1 - \frac{\sum (K_t - \hat{K}_t)^2}{\sqrt{\sum (K_t - \overline{K_t})^2}}. \quad (7)$$

Mean approximation error is the discrepancy between factual and calculated values of the resultant characteristic for each resultant parameter for each test. If the value of mean approximation error is within 5 %–7 % it is a proof of the right selection of the model for the original data.

$$A = \frac{100}{K_t} \sqrt{\frac{\sum (K_t - \hat{K}_t)^2}{n}}, \quad (8)$$

where n – the number of values of theoretical stress concentration factor.

III. Models For Determining The Theoretical Stress Concentration Factor

The section describes the models for determining the theoretical stress concentration factor for several types of common defects, considering the strength loss of PCB elements. For each model the evaluation of parameters determining its quality is also given. In this way, the models selected for determining the values of stress concentration factor can be used as a database for identifying the PCB defects [12]–[14].

Defect: Pit in the form of a circular hole (Fig. 4) in the centre of the conductor [11], [15].

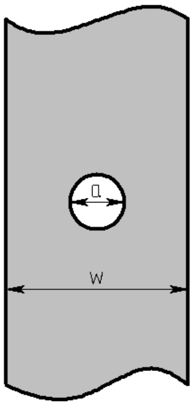

Fig. 4. Defect – circular hole.

Heywood's formula

$$K_t = 2 + \left(1 - \frac{a}{w}\right)^3,$$

where a – hole diameter; w – conductor width.

True for the whole range of change $\frac{a}{w}$.

Howland's formula

$$K_t = 2 + 0.284\left(1 - \frac{a}{w}\right) - 0.600\left(1 - \frac{a}{w}\right)^2 + 1.32\left(1 - \frac{a}{w}\right)^3,$$

According to Howland's graph,

$$K_t = 3.1981 + 4.6976\left(\frac{a}{w}\right) - 0.0392\left(\frac{a}{w}\right)^2 + 0.0001\left(\frac{a}{w}\right)^3.$$

For this formula:

$$r = 0.8165;$$

$$R^2 = 0.666;$$

$$A = 2.02\,\%.$$

Defect: Pit in the form of a circular hole (Fig. 5), shifted relatively the centre of the conductor [12], [16]–[17].

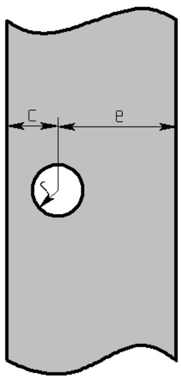

Fig. 5. Defect – shifted circular hole.

Variant 1

According to Shostrem's analytical results:

1) When $\frac{e}{c} = 1$ and $\left(0 \le \frac{r}{c} \le 0.5\right)$

$$K_t = -4.1495\left(\frac{r}{c}\right)^3 + 535080\left(\frac{r}{c}\right)^2 - 3.4046\left(\frac{r}{c}\right) + 3.0028.$$

For this formula:

$$r = 0.9999;$$

$$R^2 = 0.9998;$$

$$A = 0.12\,\%.$$

2) When $\frac{e}{c} = 2{,}4$ and $\left(0 \le \frac{r}{c} \le 0.5\right)$

$$K_t = -4.0213\left(\frac{r}{c}\right)^3 + 5.6807\left(\frac{r}{c}\right)^2 - 3.3973\left(\frac{r}{c}\right) + 3{,}0018.$$

For this formula:

$$r = 0.9999;$$

$$R^2 = 0.998;$$

$$A = 0.12\,\%.$$

3) When $\frac{e}{c} = \infty$ and $\left(0 \le \frac{r}{c} \le 0.5\right)$ for any combination of shifts.

$$K_t = -3.4024\left(\frac{r}{c}\right)^3 + 4.848\left(\frac{r}{c}\right)^2 - 3.3292\left(\frac{r}{c}\right) + 3.0018.$$

For this formula:

$$r = 0.9999;$$

$$R^2 = 0.998;$$

$$A = 0.11\%.$$

Variant 2

According to empirical formula:

$$K_t = C_1 + C_2\left(\frac{r}{c}\right) + C_3\left(\frac{r}{c}\right)^2,$$

where C_i – coefficients determined by the formulas:

$$C_1 = 2.989 - 0.0064\left(\frac{c}{e}\right);$$

$$C_2 = -2.872 + 0.095\left(\frac{c}{e}\right);$$

$$C_3 = 2.348 + 0.196\left(\frac{c}{e}\right).$$

Defect: Pit in the form of a horizontal hole (Fig. 6) of ellipse shape in the centre (along the conductor's length)

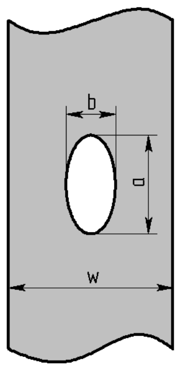

Fig. 6. Defect – horizontal hole.

Isida's graph

When $\frac{b}{a} = \frac{1}{2}$ and $\left(0 \le \frac{b}{w} \le 1\right)$,

$$K_t = -0.3952\left(\frac{b}{w}\right)^3 + 1.6764\left(\frac{b}{w}\right)^2 - 1.2862\left(\frac{b}{w}\right) + 1.9619.$$

For this formula:

$$r = 0.9691;$$

$$R^2 = 0.9391;$$

$$A = 1.07\,\%.$$

Defect: Pit in the form of a vertical hole (fig.7) of the ellipse shape in the centre (across the conductor's length) [18], [19].

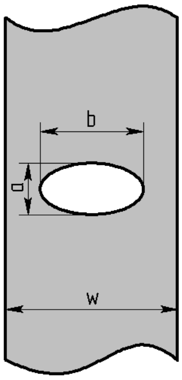

Fig. 7. Defect – vertical hole.

Variant 1
Isida's graph

1) When $\frac{b}{a} = 2$ and $\left(0 \le \frac{b}{w} \le 1\right)$,

$$K_t = -2.659\left(\frac{b}{w}\right)^3 + 5.0896\left(\frac{b}{w}\right)^2 - 5.4076\left(\frac{b}{w}\right) + 5.024.$$

For this formula:

$$r = 0.9997;$$

$$R^2 = 0.995;$$

$$A = 0.5\,\%.$$

2) When $\frac{b}{a} = 4$ and $\left(0 \le \frac{b}{w} \le 1\right)$,

$$K_t = -7.671\left(\frac{b}{w}\right)^3 + 11.474\left(\frac{b}{w}\right)^2 - 10.717\left(\frac{b}{w}\right) + 9.028.$$

For this formula:

$$r = 0.9983;$$

$$R^2 = 0.9965;$$

$$A = 1.46\,\%.$$

3) When $\frac{b}{a} = 8$ and $\left(0 \le \frac{b}{w} \le 1\right)$,

$$K_t = -16.61\left(\frac{b}{w}\right)^3 + 22.279\left(\frac{b}{w}\right)^2 - 20.294\left(\frac{b}{w}\right) + 17.07.$$

For this formula:

$$r = 0.9993;$$

$$R^2 = 0.9986;$$

$$A = 2.36\,\%.$$

Variant 2

According to analytical formula, when $1.0 \le \frac{b}{a} \le 8.0$,

$$K_t = C_1 + C_2\left(\frac{b}{w}\right) + C_3\left(\frac{b}{w}\right)^2 + C_4\left(\frac{b}{w}\right)^3,$$

where C_i – coefficients, determined by the formulas:

$$C_1 = 1.109 - 0.188\sqrt{\frac{b}{a}} + 2.086\frac{b}{a};$$

$$C_2 = -0.486 + 0.213\sqrt{\frac{b}{a}} - 2.588\frac{b}{a};$$

$$C_3 = 3.816 - 5.510\sqrt{\frac{b}{a}} + 4.638\frac{b}{a};$$

$$C_4 = -2.438 + 5.485\sqrt{\frac{b}{a}} - 4.126\frac{b}{a}.$$

IV. Conclusion

PCB conductive pattern defects accumulate stresses leading to strength loss during operation life. The formulas are given that link the geometry of defects and the stress concentration factor, corresponding to four types of defects. These formulas are necessary for determining the number of cycles and time to failure, fatigue strength coefficient.

Actual defects of PCB conductive pattern have various forms and sizes. In real life, it is next to impossible to predict all possible types of actual defects. The article offers the formal approach to defect study, which allows reducing their number and automating the process of predicting their development during software realization.

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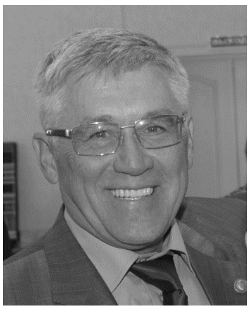

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