Post-processing improvement of lock-in thermography study of MCM-L for better hidden defect localization

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Received: April 3, 2021. Revised: February 27, 2022. Accepted: March 15, 2022. Published: March 30, 2022.

Abstract—This paper examines the impact of postprocessing of lock-in thermographic measurement data on the ability to detect and characterize in terms of geometric dimensions and location of specific types of defects in MCM-L. A thermal 3D model of a test specimen with hidden artificial defects is used and simulated lock-in thermography measurement is performed. Qualitative and quantitative assessment was performed of the correct detection and geometric dimensions characterization of the defects. The Shape Difference (SD) criteria was defined and used for qualitative and quantitative assessment of the confidence detection and characterization of defects in MCM-L. A Window Sliding Offset (WSO) approach is performed as method for improvement of the defects characterization quality. This study revel that providing information on the depth and shape of defects through the combined use of infrared thermography measurement and 3D thermal modeling can be used to determine the desired confidence levels of defects detection.

Keywords—hidden defects, lock-in thermography, multichip modules, MCM-L, thermal simulation

I. INTRODUCTION

USAGE of multi-chip modules leads to a significant reduction in the size of electronic equipment. The multichip modules are classified mainly according to the type of substrate on which the electronic components are mounted (C-, D- and L-type) [1], [2].

A very important stage in the production of electronic products is testing and diagnostics to detect defects. The most typical tests that are performed are electrical tests. They can be used to check the electrical behavior of a unit or the entire product in all possible modes of operation. The result of this study is an assessment of the workability of the product. In general, the results of electrical testing do not provide enough information about the reliability of the product, as well as the presence of some defects that at the time of manufacture do not affect the workability of the device, but in the future may cause damage. Electrical testing can also be performed at an earlier stage of production, for example in the production of the substrate. The result of this testing provides mainly information only on the presence of conductive track interruptions as well as short circuits. In order to achieve higher reliability of the products, defects that could lead to damage in the future, must be found during production. For example, for substrates, these are a track with a reduced cross section, delamination of the layer, the presence of air cavities in the insulation layers.

Detection of this type of defect requires non-destructive noncontact methods by which information on the internal structure of the test specimen can be obtained. Infrared thermography is a widely used method in the field of electronics for non-contact and non-destructive diagnostics [3], [4], [5]. Infrared thermography is widely studied in terms of its application in many areas and the processing of thermographic data [6], [7], [8], [9]. Hidden defects can be detected by using of active thermography methods, in which additional thermal stimulation of the studied object is performed during thermographic recording and the obtained data are processed [4]. The main active thermography methods are pulse, transient and lock-in thermography [4]. In general, lock-in thermography has the most advantages, but also more complex technical implementation.

In some cases, the use of active infrared thermographic

methods can also detect defects associated with conductive tracks - interruptions, short circuits and others.

Reliable detection of a defect using active thermography depends on one side of the measurement parameters (for example, in lock-in thermography, these are the lock-in frequency, the heat flux generated by the excitation source, the duration of the measurement, the camera frame rate) and from the processing on the other hand.

Most often, the result of the diagnosis for defects is of the type There is / There is no a defect and if the result is that there is a defect, where is this defect. Additionally, in some cases, the dimensions and type of defect can be determined (based on temperature data).

Defining the criteria for the presence of a defect, as well as whether the available data allow the correct characterization of the defect is a complex task and its solution requires an individual approach. Characterization has many influencing factors in determining a parameter, such as the influence of the size of the defect in determining its depth [10].

In our previous study, it was found that it is possible that in a correct measurement setup and correctly selected measurement parameters, it is not possible to detect or characterize defects after processing [11]. This article discusses methods that can avoid the inability to detect the defect and to improve phase contrast. However, the application of these methods also affects the sharpness of the phasegrams, which is directly related to the correct characterization of the defect in terms of geometric dimensions and location. In the current article we will consider the influence of post-processing on the correct determination of the geometric dimensions and location of specific types of defects in MCM-L substrates. In lock-in thermography, in general, the processing is quite complex and it is necessary to choose values for many parameters, without universal guidelines for this. The study will be done for the window sliding approach discussed in [11], for which a very significant impact on the processing result was found.

A used thermal model of a test specimen with hidden artificial defects is presented in section II. The criteria for detecting defects are defined in section III. Qualitative and quantitative assessment was performed for the correct detection and characterization in terms of geometric dimensions and location of defects when applying the window sliding approach, considered in our previous study [11]. The results are presented in section IV.

II. THERMAL MODEL OF THE TEST SAMPLE

A thermal model of a test sample considered in our previous study was used [12]. The model is developed using the widely used specialized software product for modeling and simulation of thermographic measurements ThermoCalc 3D [13]. Fig. 1 shows the topology and layers structure of the test sample.

The test sample contains two hidden layers. There are three types of hidden defects. Each type of defect occurs in four variants:

- Depth of 0.35 mm without overlapping with the other layer;
- Depth of 0.35 mm with overlap with the other layer;

- Depth of 0.67 mm without overlapping with the other layer;
- Depth of 0.67 mm with overlap with the other layer.

In this way, both the influence of the depth at which the defect is located and the influence of another layer located in the same area but at different depths can be studied. A more detailed information about the test sample can be found in [12].

The thermal model (in ThermoCalc 3D) of the test sample in the environment of ThermoCalc 3D is shown in Fig. 2. Two different views of the test sample model are shown. The horizontal and vertical location of the defects is shown.



Fig. 2 Views in ThermoCalc 3D of the thermal model of the test sample

INTERNATIONAL JOURNAL OF CIRCUITS, SYSTEMS AND SIGNAL PROCESSING DOI: 10.46300/9106.2022.16.115

III. DESCRIPTION OF DEFECTS AND CRITERIA FOR THEIR DETECTION

Detection of defects is performed on the basis of the obtained phase profile from simulation lock-in thermographic measurement. In fig. 3 are shown the profiles (blue lines) on which the defects are detected. Profiles include the values of the closest pixels to this line. The assessment of the correct detection of defect 1 and defect 3 is performed by assessing the detection of the edges of the defect (l_{E1} and l_{E2}) and the defect as a whole. In Defect 2, the edges are not detected separately, as they are located very close to each other.



Tig. 3 The thermal model of the test sample (views i ThermoCalc 3D)

The assessment for the correct determination of the defect shape is performed by calculating a parameter that will be marked with *SD* (Shape difference). This parameter shows how much the obtained phase profile for the defect or for a given defect element differs from the theoretical one, which would ideally be obtained. Fig. 4 shows the limits for which the assessment is performed for each element of the defect. The ideal profile is shown in blue and the hypothetical real profile in red. Actual profiles obtained in the present study will be shown in the Results section.

At the edge of the defect, the change can be either an increase in phase or a decrease. This is detected during processing and the calculation is corrected automatically. The figure shows only the case when the phase increases in the area of the left boundary and decreases in the area of the right boundary.

For defects 1 and 3, the *SD* for the elements and for the whole defect is calculated as follows (for the case shown):

$$SD_{E1} = \sum_{i=k(l_{E1})-6}^{k(l_{E1})-1} (\Phi_i) + \sum_{i=k(l_{E1})}^{k(l_{E1})+6} (\Phi_i - 1),$$
(1)

$$SD_{E2} = \sum_{i=k(l_{E2})-6}^{k(l_{E2})} (\Phi_i - 1) + \sum_{i=k(l_{E2})+1}^{k(l_{E2})+6} (\Phi_i),$$
(2)

$$SD_{full} = \sum_{i=k(l_{E_1})-6}^{k(l_{E_1})-1} (\Phi_i) + \sum_{i=k(l_{E_1})}^{k(l_{E_2})} (\Phi_i - 1) + \sum_{i=k(l_{E_2})+6}^{k(l_{E_2})+6} (\Phi_i), \quad (3)$$

where $k(l_{E1})$, $k(l_{E2})$ and $k(l_E)$ are the nearest to l_{E1} , l_{E2} and l_E pixel number of the profile, and Φ_i is the normalized phase value (in the range between 0 and 1) for pixel with number *i*.

For defect 2, SD is calculated as follows:

Fig. 4. The limits for which the assessment of each defect element is performed: (a) Defect 1; (b) Defect 2; (c) Defect 3

The calculated *SD* parameter can be used to quantify how correctly the geometric dimensions of the defect and its location in the sample are determined, as well as a qualitative assessment of the defect detection. In this case, a limit value of *SD* has been selected, above which it is considered that the defect has not been detected. Above this value, in addition to the unacceptable error in determining the geometric dimensions and location of the defect, there is a risk of false detection (there is an examples in Fig. 8 and Fig. 9). In our case, the following limits have been selected, where the defect is considered to be found and the error in determining its location and geometric dimensions is acceptable:

$$0 < SD_{E1} < 2; 0 < SD_{E2} < 2; 0 < SD_{full} < 5.$$
⁽⁵⁾

The phase of the temperature signal for each pixel of the profile are calculated as follows [12]:

$$S^{F} = \frac{1}{I_{last} - I_{first} + 1} \times \sum_{i=I_{first}}^{I_{last}} (F_{i} \times K^{F}),$$
(6)

$$K^F = -2 \times e^{-j\frac{2 \times \pi \times (i-1)}{n}},\tag{7}$$

$$n = f_{frame} \times \frac{1}{f_{lock-in}},\tag{8}$$

$$I_{last} = N \times n - WSO, \tag{9}$$

$$I_{first} = I_{last} - N_{comp} \times n - WSO, \tag{10}$$

$$\Phi = \arctan\left(\frac{Im(S^F)}{Re(S^F)}\right),\tag{11}$$

where F_k is the *i*-th time value of the temperature signal, I_{first} and I_{last} are the first and last index of temperature signal values, which is used the processing, n is the number of time values for temperature signal for one lock-in period, N is the number of periods, N_{comp} is number of periods which is used in processing, WSO is the window sliding offset $(WSO = 0 \div (n - 1))$ and Φ is the calculated phase.

The parameters of lock-in thermography simulated measurement are presented in Table 1.

parameter	value
lock-in frequency (f _{lock-in} [Hz])	0.1
frame rate (<i>f</i> _{frame} [Hz])	10
number of periods (N)	5
number of periods used in computation (<i>N_{comp}</i>)	4
average heat flux though test sample $(q_{excitation} [W m^{-2}])$	550
image resolution [pixels]	240×240

Table. 1 parameters for lock-in thermography study

IV. RESULTS

For each defect, the *SD* parameter is calculated for all possible window sliding offset (*WSO*) values. Their number is equal to the number of thermograms taken during a one lock-in period, which is determined by equation (8). The limits within which the *WSO* changes are $0 \div (n - 1) = 0 \div 99$.

Results for the four variants for each defect in terms of depth and overlap are presented.

Fig. 5 shows the results for defect 1. In Fig. 6 shows the results for defect 2. Fig. 7 presents the results for defect 3.

The limits of *SD* defined by equation (5) are represented graphically in the figures. The range of successful detection and characterization of the defect is given in green, and the range of

unsuccessful detection and characterization of the defect is given in red.

The significant influence of the WSO parameter is evident from the presented results. It can be seen that in some values it is impossible to detect the defect, while in others the SD parameter has a low enough value for correct detection and characterization of the defect. This means, on the one hand, that a given measurement may come across such a piece of data that it is impossible to detect and characterize defects. On the other hand, that by changing the part of the data on which the processing is performed (by changing of the WSO parameter) the ability to detect and improve the accuracy in determining the geometric dimensions and location of the defect can be restored.



Fig. 5. Results for defect 1: (a) Element 1; (b) Element 2; (c) Full



Fig. 7. Results for defect 3: (a) Element 1; (b) Element 2; (c) Full

Defects located at a depth of 0.35 mm can be detected and characterized normally at a large number of *WSO* values, whether or not there is an overlap with the lower layer. There are also several values at which detection is impossible. Therefore, it is quite possible to come across such a part of the data, which would impair the possibility of detection. In this case, the application of a window sliding approach will restore the possibility of characterization. It is sufficient to recalculate only a few contiguous WSO values or even just one and to restore the ability for correct characterization of the defect. Let us come across the case corresponding to WSO = 67. In this case SD = 5,000. If we move the data window 3 frames forward (WSO = 70), then SD = 0.710.

Defects located at 0.67 mm can only be detected if there is no overlap with the upper layer. In this case, at a large number of *WSO* values, *SD* is in the red zone. This means that it is necessary to calculate the phase for a larger number of *WSO* values, and the possibility of characterization will be restored at a relatively large number of values.

For defects located at 0.67 mm in the presence of overlap with the upper layer, the application of window sliding approach can reduce the value of *SD*, but in this case, there is no value at which *SD* falls into the green zone. In this case, this is fully expected, as there is a physical obstacle to the correct detection and characterization of defects (the presence of a layer located shallower, which has many times greater impact on surface temperature). However, it can be seen that at some *WSO* values, the *SD* value can decrease significantly, so that the presence of a given defect can be assumed with a lower degree of reliability, but without a real possibility of characterization.

In order to better clarify the possibility of detecting defects and their characterization, several specific profiles will be considered. Fig. 8 shows the obtained profiles for element 1 of defect 1 without overlap for the two depths, at two *WSO* values. Fig. 9 shows the profiles for the whole defect 1 at a depth of 0.67 mm without overlap, at 4 *WSO* values.

For each profile, the *WSO* value is given, as well as the *SD* value. The value of *SD* is colored in green if the value is within the allowable limits and in red - if the value is not within the allowable limits.

It can be seen that at different WSO values, detection and characterization capabilities may differ radically. In Fig. 8, for a depth of 0.35 mm, it can be seen that the defect element 1 can be perfectly detected and quite accurately characterized, but at some WSO values it is not even possible to detect it correctly (the case shown for WSO = 12). According to the profile shown, you may mistakenly believe that there are several different defects or this is a noise effect and there is no defect in this place. For a depth of 0.67 mm, the effect is similar. In this case, however, it is not possible to achieve a high accurate characterization, which is associated with physical limitations.

Fig. 9 shows two cases in which *SD* is within acceptable limits and two - in which *SD* is not within acceptable limits. It can be seen that by changing the *WSO* value, a very good opportunity to characterize the defect can be achieved.

In general, the WSO value at which the lowest SD value is

achieved depends on the specific measurement and can only be determined experimentally by iterative phase calculation for different values. The algorithm presented in [11] can be used by adding the calculation of the *SD* parameter for different *WSO* values.



Fig. 8. Some phase profiles for defect 1, element 1: (a), (b) - at 0.35 mm; (c), (d) - at 0.67 mm



V.CONCLUSION

This paper examines the impact of post-processing of lockin thermographic measurement data on the ability to detect and characterize in terms of geometric dimensions and location of specific types of defects in MCM-L. Significant influence of post-processing on the ability to characterize defects, as well as on their detection is confirmed. The obtained results make it possible to improve the detectability and improve the accuracy in characterizing the defects in terms of geometric dimensions and location only through post-processing, without the need for additional measurements. For a more accurate assessment, it is necessary to perform these studies on real samples, which is the subject of future research. This study concluded that providing information on the depth and shape of defects through the combined use of infrared thermography measurement and 3D thermal modeling can be used to determine the desired confidence levels of defects detection by lock-in thermography diagnostics.

ACKNOWLEDGMENT

The author would like to thank for the support of National Science Fund under which Project No. DN 17/16 the present work was conducted.

References

- [1] Multi-Chip Module Market Global Industry Analysis, Size, Share, Growth, Trends and Forecast 2016 – 2024, Available online (accessed on 20 January 2022): <u>https://www.transparencymarketresearch.com/multi-chip-module-market.html</u>
- [2] Blazek R., Kautz D., Galichia, J., MCM Multichip Module Manufacturing Guide, United States Department of Energy (Honeywel, 2000), l, p. 57.
- [3] M. Lizaranzu, A. Lario, A. Chiminelli μ I. Amenabar, "Non-destructive testing of composite materials by means of active thermography-based tools," *Infrared Physics & Technology*, vol. 71, pp. 113-120, 2015.
- [4] S. Doshvarpassand, C. Wu и X. Wang, "An overview of corrosion defect characterization using active infrared thermography," *Infrared Physics & Technology*, vol. 96, pp. 366-389, 2019.
- [5] Hsieh, J., "Survey of thermography in electronics inspection," *Proceedings of the SPIE Sensing Technology* + *Applications*, Baltimore, MD, USA, May, 2014, pp. 1-12.
- [6] M. Alhammad et all., "Diagnosis of composite materials in aircraft applications: towards a UAV active thermography inspection approach," Thermosense: Thermal Infrared Applications XLIII, SPIE, 12-17 April, 2021, DOI: 10.1117/12.2586064
- [7] K. Sreeshan, R. Dinesh, K. Renji, "Nondestructive inspection of aerospace composite laminate using thermal image processing," SN Appl. Sci., issue 2, article no 1830 (2020). <u>https://doi.org/10.1007/s42452-020-03619-9</u>
- [8] A. Katunin, "A Concept of Thermographic Method for Non-Destructive Testing of Polymeric Composite Structures Using Self-Heating Effect," Sensors (Basel). 2018 Jan; 18(1): 74, DOI: 10.3390/s18010074
- [9] E. D'Accardi, D. Palumbo, R. Tamborrino, U. Galietti, Quatitative analysis of thermographic data through different algorithms, Procedia Structural Integrity, vol. 8 (2018), pp. 354-367
- [10] S. Hiasa, R. Birgul, F.N. Catbas, "Effect of Defect Size on Subsurface Defect Detectability and Defect Depth

Estimation for Concrete Structures by Infrared Thermography," J. Nondestruct. Eval. Vol. 36, no 57 (2017), DOI: <u>https://doi.org/10.1007/s10921-017-0435-3</u> [11]Stoynova, A., Bonev, B., "Improvement the post-

- [11] Stoynova, A., Bonev, B., "Improvement the postprocessing quality in lock-in thermography," *Int. J. of Circuits, Systems and Signal Processing*, Vol. 13 (2019), pp. 20-27.
- [12] A. Stoynova, B. Bonev, S. Andreev, N. Spasova, "Nondestructive Thermal Diagnostics of Multilayer Substrates for Multichip Modules", 2021 IEEE 23rd Electronics Packaging Technology Conference (EPTC), ISBN: 978-1-6654-1619-1, DOI: 10.1109/EPTC53413.2021.9663919
- [13] V. Vavilov, "Three-dimensional analysis of transient thermal NDT problems by data simulation and processing", Proceedings of SPIE - The International Society for Optical Engineering, Vol. 4020, 2000, pp. 152-163.

Sources of funding for research presented in a scientific article or scientific article itself National Science Fund of Bulgaria

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