Metrol. Meas. Syst., Vol. XXII (2015), No. 4, pp. 521–530.

METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.pg.gda.pl

A METHOD OF CALCULATING THERMAL DIFFUSIVITY AND CONDUCTIVITY FOR IRREGULARLY SHAPED SPECIMENS IN LASER FLASH ANALYSIS

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Abstract

The Low Temperature Joining Technique (LTJT) using silver compounds enables to significantly increase the thermal conductivity between joined elements, which is much higher than for soldered joints. However, it also makes difficult to measure the thermal conductivity of the joint. *The Laser Flash Analysis* (LFA) is a non-intrusive method of measuring the temperature rise of one surface of a specimen after excitation with a laser pulse of its other surface. The main limitation of the LFA method is its standard computer software, which assumes the dimensions of a bonded component to be similar to those of the substrate, because it uses the standard Parker's formula dedicated for one-dimensional heat flow. In the paper a special design of measured specimen was proposed, consisting of two copper plates of different size joined with the sintered silver layer. It was shown that heat properties of these specimens can also be measured after modifying the LFA method. The authors adapted these specimens by masking the false heat signal sourced from the uncovered plate area. Another adaptation was introducing a correcting factor of the heat travel distance, which was calculated with heat-flow simulations and placed into the Parker's formula. The heat-flow simulated data were compared with the real LFA measurement results, which enabled estimation of the joint properties, *e.g.* its porosity.

Keywords: thermal diffusivity, LFA, LTJT joints, high power electronics.

1. Introduction

The emerging market of high power and high temperature semiconductor devices implies a new advanced method of packaging. Semiconductors for high energy applications, like *Insulated Gate Bipolar Transistor* IGBT, or *Gate Turn Off Signal Controlled Rectifier* GTO SCR, are now widely available. *The Low Temperature Joining Technique* (LTJT) method of joining, using silver compounds, enables a significant increase of the thermal conductivity between joined elements, *i.e.*, the bonded element and the heat spreader. The thermal conductivity of LTJT joints is much higher than that of soldered joints. On the one hand it enables to spread more heat from the active component, but on the other hand makes it difficult to measure the thermal conductivity of the bonded layer. A steady state contact method of measuring thermal conductivity, like the Searle's bar method, is not adequate due to a high thermal interface resistance between the bar and the specimen surface. Therefore, non-intrusive methods of measurement are considered. One of them is the *Laser Flash Analysis* (LFA) which is a contactless transient method of measuring the heat diffusivity of materials, which can be further converted to the thermal conductivity.

The usual specimen configuration is shown in Fig. 1 [1]. If we heat the bottom face of that specimen with a laser pulse, the heat spreads upwards to the top face, rises the temperature

Article history: received on Feb. 02, 2015; accepted on Jul. 18, 2015; available online on Dec. 07, 2015; DOI: 10.1515/mms-2015-0043.

and generates increased IR radiation, that is detected with an IR sensor. The delay between the laser pulse and the temperature rise at the top surface determines the heat diffusivity of a tested material.

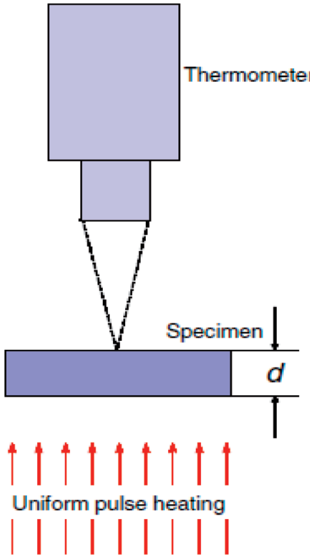


Fig. 1 The basic configuration of the laser flash method [1].

An analytical solution for laser flash thermal diffusivity measurements has been given by Parker *et al.* [2] assuming the following conditions:

1) The duration of laser pulse is negligibly short compared with the characteristic time of heat diffusion.
2) The bottom face of specimen is uniformly heated by a pulse of light.
3) The specimen is adiabatic during the measurement after heating by the pulse of light.
4) The specimen is uniform (in geometry) and homogeneous.
5) The specimen is opaque (nontransparent and non-translucent) to the pulse of light and to thermal radiation.

If these conditions are met, the heat flux becomes one-dimensional and the temperature of the top face of specimen changes according to the (1) proposed by Carlsav and Jaeger [3]:

$$T(z,t) = \frac{Q}{\rho C_p d}\left[1 + 2\sum_{n=1}^{\infty}(-1)^n exp\left(-(\pi n)^2 \frac{t}{\tau_0}\right)\right], \quad (1)$$

where: Q is the total energy absorbed by the specimen; C_p is the heat capacity of the specimen; $\tau_0 = d^2/\alpha$ is the characteristic time for diffusion of heat across the specimen; α – the thermal diffusivity of the specimen; and d – the specimen thickness. τ_0 can be calculated from (1), that gives the relationship (2) proposed by Parker [2]:

$$\tau_0 = t_{1/2}/0.1388, \quad (2)$$

where: $t_{1/2}$ – the duration oflaser pulse up to reaching half of the maximum temperature on the backside. Then, the Parker's formula (2) is converted into its final form (3), as shown in [2]:

$$\alpha = 0.1388\frac{d^2}{t_{1/2}}, \quad (3)$$

Equation (3) is easily applicable to the thermal characterization of materials tested by the LFA method. If this method is adapted to measure properties of heterogeneous specimens, like joints between the component and the substrate, taking into account their porosity [4, 5], the condition (IV) requires the lateral dimensions of the bonded component to be the same as the substrate. Otherwise, the heat flux would be no longer uniform, which would make the thermal conductivity calculation difficult.

Thermal testing of LTJT specimens has a serious limitation. Usually, the bonded components are significantly smaller than the bonded substrate. This size disproportion is very advantageous for the applied method of joining, otherwise the disability to obtain sufficient bonding pressures and poor evacuation of pores from the middle area of the joint are serious limitations for large bonded components [6]. Bonding small (up to 2 mm x 2 mm) components to a substrate of the same size is also very limited due to difficult paste depositions and specimen size limitations in the commercial LFA equipment, that requires the minimum lateral size of a measured specimen to be much bigger than the typical die. In the case of the Netzch LFA 457 equipment used in our research, the minimal size of a specimen in X–Y directions is 8 mm x 8 mm.

In the presented paper the Parker's method of characterisation of the thermal diffusivity of materials was adapted for specimens consisting of two different lateral size cubes and a joint between them.

2. Specimens and measurement equipment

The method of extracting the thermal properties of a joint from the measurement of the whole multi-layered specimen requires using well heat conducting materials for the bonded materials. To meet these requirements copper cubes were used instead of commonly used Direct Bonded Copper on ceramic.

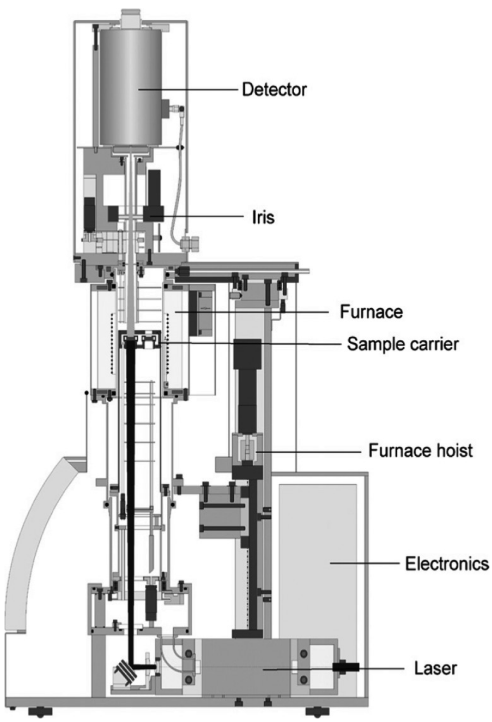


Fig. 2. The measurement part of the NETZSCH LFA 457 MicroFlash [8].

Each test specimen, used in experiments, consists of 3 parts: a 35 or 50 micron bonding layer that bonds the bottom copper plate (8 mm x 8 mm wide and 0.8 mm thick) with the upper plate (2 mm x 2 mm wide and 0.8 mm thick). The bonding procedure was described in [7].

The LFA was proceeded using the NETZSCH 457 MicroFlash unit configured as shown in Fig. 2. During the LFA measurement procedure of a specimen, where the upper part is smaller than the lower part, the IR signal is emitted both from the bonded upper plate and from the large area of the bottom plate (Fig. 3a) The latter area is 15 times larger than that of the upper surface the useful signal is collected from. The signal from the bottom plate is not altered by the measured joint; therefore it is useless. Moreover, it masks the proper signal from the upper plate.

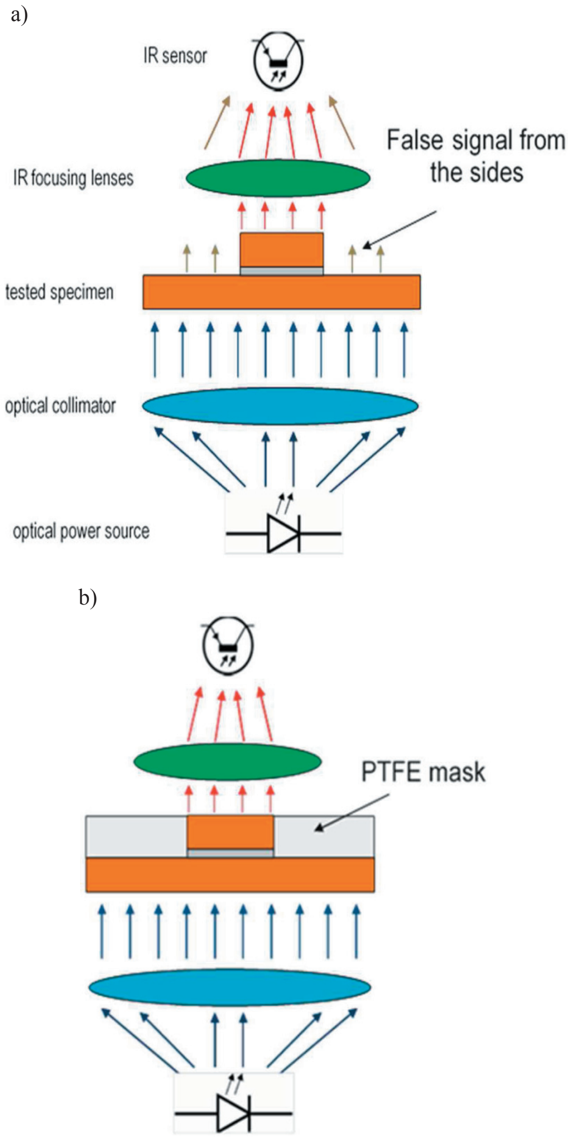


Fig. 3. a) The schematic of LFA measurement of irregularly shaped specimen without a mask; b) the schematic of LFA measurement of irregularly shaped specimen with the PTFE mask.

The authors have developed a method of filtering-out this false signal. The authors prepared a Politetrafluoroetylen (PTFE) mask that covers the bottom plate surface and blocks its IR signal to the sensor (Fig 3b). Then, the only IR signal detected comes from the upper plate.

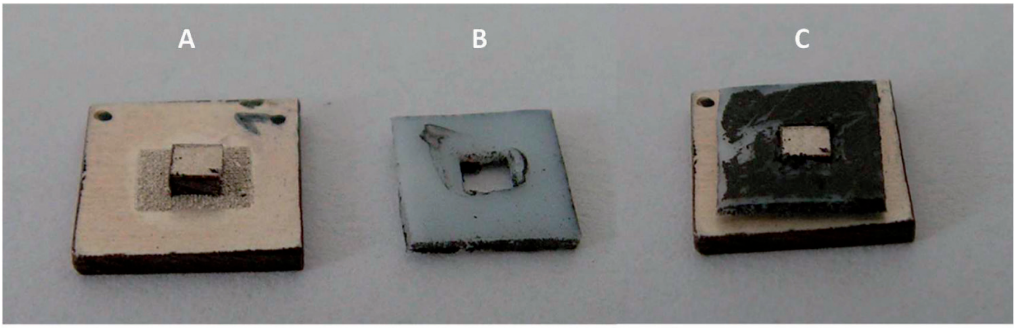


Fig. 4. a) The test specimen; b) the PTFE mask; c) the specimen covered with the PTFE mask.

An 8 x 8 mm specimen (Fig. 4a) was covered with the 6 x 6 mm PTFE mask shown in Fig. 4b. Its size is sufficient to block out the unnecessary signal from the surface, due to the fact that the collection area in the LFA equipment used in the experiment – Netsch 457 – has a 5 mm collection diameter. Finally, the temperature signal is caused only by the heat flux that passes through the bottom plate, the bonding layer and through the upper plate carrying information about the heat properties of the bonding layer.

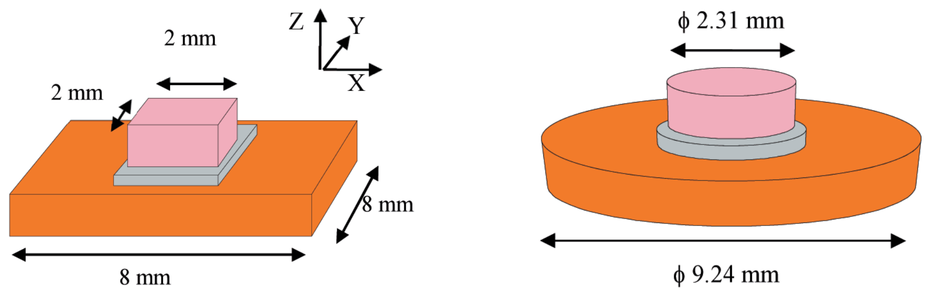
The other problem that still needs to be solved is the non-uniform density across the heat flux. The shape of a specimen causes a heterogeneous thermal flux in the tested structure and has components in three directions. That is why the direct interpretation of the measurement results is impossible. Two components of the heat flux are present. The flux in the Z direction along the laser – IR sensor axis, which is required for this measurement method, and the flux in the planar direction along the radial lines, meeting at the middle point of the specimen. The heat flux in the planar direction significantly increases the propagation time of the temperature signal, which – according to the Parker's equation – lowers the diffusivity results if the specimen thickness is valid for the Z direction only. The actual travel distance of the heat is non-uniform and difficult to extract from the specimen's geometry.

A similar problem with the non-uniform heat flux was described in [9], where the hot wire probe method of measuring thermal properties was applied. The heat source and the temperature sensor were placed in parallel with a cubic specimen in a certain distance. That caused a significant heat flux depending on the position. The problem of calculating the heat properties in that system was overcome by simulating a network of finite elements in MATLAB environment. To solve a similar problem in our case, the network of finite elements was created and computer simulation of a heat flux was performed with the SPICE simulator.

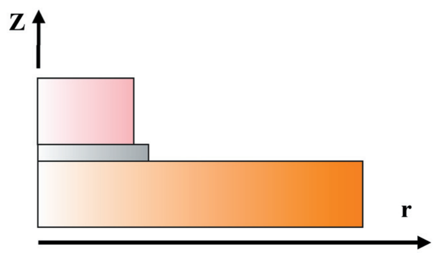
3. Modelling of thermal properties

A commonly used RC model of heat transfer was applied. This model can be easily calculated with use of electric simulation software due to an analogy between the electrical and heat properties. The simulations of a heat transfer with use of the RC Spice model were also performed in [10]. Generally, the heat flux proceeds in 3 dimensions, which makes the computer simulations complicated and time-consuming. In the particular case of this specimen, significant simplifications can be done. As a solution, simulation of the thermal and electrical flux in the tested structure was proposed. In a general case it is very complex and requires creation of a full three-dimensional test structure. Due to the properties of software (SPICE), which is very inefficient in creating and simulating 3D networks, a significant simplification was made.

a)



c)



d)

$$C_{p2D}® = 2\pi * r * C_p, \qquad (2)$$

$$\lambda_{2D}® = 2\pi * r * \lambda, \qquad (3)$$

$C_{p2D}®$ – the two-dimensional heat capacity for for a given distance r;
$\lambda_{2D}®$ – the two-dimensional thermal conductivity for a given distance r;
C_p – the specific heat capacity;
r – a deviritive of the area of radius r

e)

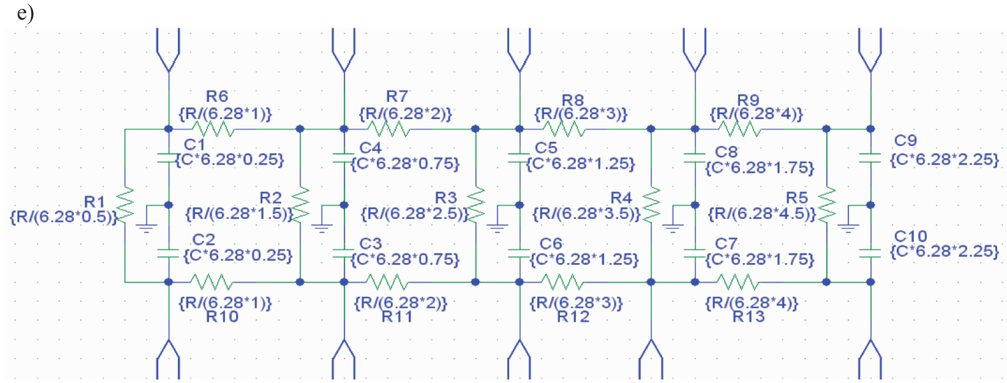


Fig. 5. The steps of building a model of thermal properties.

Firstly, transformation of the rectangular elements (Fig. 5a) onto a cylinder block (Fig. 5b) was made in such a way that each of the layers of the rectangular model was replaced with a cylinder of the same height, with unchanged thermal properties of the material. The diameter of the cylinders was chosen to keep the volume of the components corresponding with their mass. The next step is transformation of the cylinder component onto a plane (Fig. 5c). The basis for this transformation is the rotational symmetry of the laser spot, infrared detector and probes used for the electrical characterization. Thus, it can be assumed that the heat flux

- 10.1515/mms-2015-0043

contains only its vertical Z and radial r components, so that they can be presented on the cross-sectional plane. So, the uniform physical properties $C_{p,}$ λ were transformed onto the gradient values $C_{p2D}(r)$, $\lambda_{2D}(r)$, that depend also on the distance r from the centre of the structure. The physical properties of the material, lying on the circle with a given radius r and position Z, are grouped into a single point, so that the effective property is multiplied by the circumference length of the circle with radius r. The equations used for these transformations are expressed by the formulas in Fig. 5d. The structure was modelled in the SPICE simulator by a mesh of nodes, where an adjacent resistance of resistor represents the unitary heat conductivity $\lambda_{2D}(r)$ in the two-dimensional coordinate system. Also, for each of the nodes, the capacitance of a capacitor $C_{p2D}(r)$ symbolizes the unitary heat capacity after transformation into 2D. An example of such a structure is shown in Fig. 5e.

For the substrate and the die the thermal properties of bulk copper blocks were assumed. The thermal properties of the joint were described by the joint porosity after the sintering stage. The porosity of the joint linearly affects the heat capacity which is the direct consequence of the dependence of density on porosity, so that the effective heat capacity can be expressed by (4):

$$C_{pJ} = (1 - \phi_P)*C_{P(Ag)} / 100\%, \tag{4}$$

where: C_{pJ} – the effective heat capacity of sintered joint; $C_{P(Ag)}$ – the heat capacity of bulk silver; ϕ_P – the percentage of porosity.

Generally, the heat conductivity depends on the porosity, shape and pore distribution. To simplify this relation, it was assumed that the thermal conductivity depends linearly on the porosity complement to one:

$$\lambda_J = (1 - \phi_P)*\lambda_{(Ag)} / 100\% , \tag{5}$$

where: λ_J – the effective thermal conductivity of sintered joint; $\lambda_{(Ag)}$ – the thermal conductivity of bulk silver; ϕ_P – the percentage of porosity.

Two SPICE models of test structures were created. One model has an irregular shape, as shown in Fig. 5, and the other is regular with a rectangular shape, where both joined pieces are of the same size. The joint porosities of 0%, 25% 50%, 75%, and the joint thicknesses of 25, 50, 100 microns were assumed. The effective values of C_{pJ} and λ_J were calculated according to (4) and (5) and then transformed onto a two-dimensional coordinate system using (2) and (3).

The excitation signal used for simulation was a square wave with the duration of 1 microsecond and the peak output of 1 kW, giving the total energy of 1 mJ. The direct measurement of the laser pulse in a real LFA equipment was also recorded. Its shape is presented in Fig. 6. The time point when the pulse reaches half of its total energy was taken as 0. Its total duration is still acceptably short, comparing to the half-width delay $t_{1/2}$ recorded for the real specimens.

The bottom face temperature versus time-since-excitation for both models were simulated as shown in Fig. 7. The half-maximum time $t_{1/2}$ values are obtained from the simulation curves and are shown in Table 1. The half-maximum time values for real specimens obtained by the LFA are also shown in Table 1 for comparison.

The simulated half-maximum time values for the irregularly shaped models are longer by a factor of 1.36 than for the regularly shaped ones, regardless of the porosities, joint thicknesses within the range of 35–100 microns. According to the Parker's formula, this prolongation can be explained by an extended heat travel distance by a factor of 1.17. The estimated LTJT joint porosity of a real specimen was obtained by comparison of the actual measurement data with the simulated values – to be just below 25%.

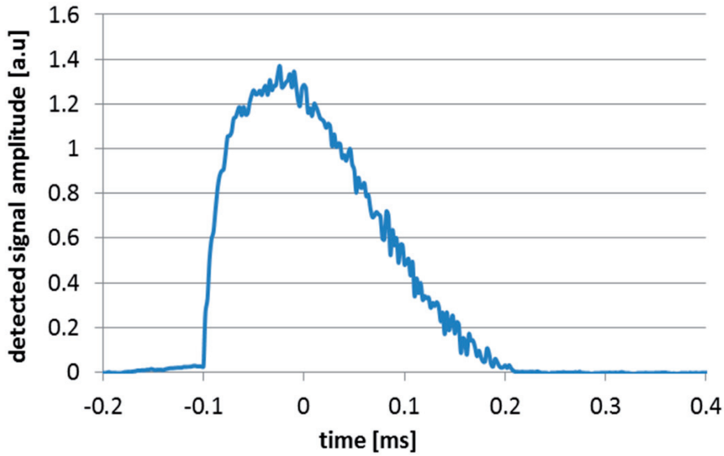


Fig. 6. A shape of the detected signal with a direct laser excitation.

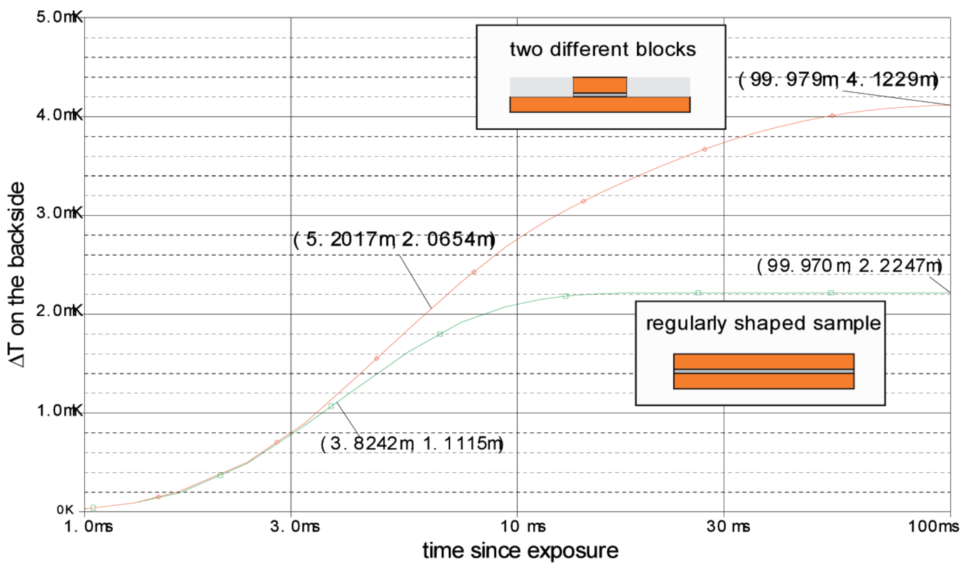


Fig. 7. The simulated rise of the top face temperature for regularly and irregularly shaped specimens.

Table 1. The comparison of modelled and measured time to half of the maximum.

joint thickness, um	shape of specimen	simulated $t_{1/2}$, ms for assumed joint porosity, ϕ_P					measured $t_{1/2}$, ms
		0%	25%	50%	75%	87%	
35	regular	3.74	3.82	3.93	4.16	4.56	–
	irregular	5.09	5.20	5.34	5.66	6.21	5.19
50	regular	4.01	4.10	4.23	4.49	4.92	–
	irregular	5.45	5.58	5.75	6.11	6.69	5.55
100	regular	4.11	4.18	4.36	4.69	5.08	–
	irregular	5.59	5.69	5.93	6.37	6.91	–

- 10.1515/mms-2015-0043

Finally, the Parker's (3) for that specific combination of top and botom plate geometries can be transformed into (6).

$$\alpha = 0.1388 \cdot \frac{(d \cdot 1.17)^2}{t_{1/2}} = 0.1888 \cdot \frac{d^2}{t_{1/2}}. \quad (6)$$

Equation (6) includes the effective increase of heat travel distance by a factor of 1.17.

4. Conclusions

The main goal was to measure heat properties of the bonding layer between two unequal size copper plates by the LFA. Due to the size mismatch of the plates, the standard LFA test procedure could not be applied because of two reasons: 1) the false signal from the larger plate reaching the detector without flowing through the joint, and 2) the planar component on the heat flux that extended the heat travel distance and – further – the time delay of the temperature signal collected from the top plate. The first problem was solved by masking the bottom plate surface that is heading towards the detector, with a heat insulator. The second problem was solved by creating a heat model of the specimen. Due to the symmetry of this model, some simplifications were applied, that enabled to create a two-dimensional mesh of nodes instead of a tree-dimensional one. That speeded up the simulations and enabled to use computer software dedicated for modelling electrical circuits. The model enabled to obtain the half-maximum time values for various heat properties of the joint, resulting from e.g. the sintered joint porosity. These values can be compared with the real results of the LFA, enabling to estimate the real heat properties of the bonding layer. For this specific shape of the measured specimen, a correction factor for the heat travel distance was obtained, which enables to modify the standard Parker's (6) and then interpret the LFA data without a need for heat flow simulations.

Acknowledgements

This work was partially financed by the European Union within the NCBR project No. UOD-DEM-1-215/001.

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