Application of Comsol Multiphysics in the Study of Heat Transfer in Solids: Comparation with Measurements Obtained by Means of Infrared Photothermal Radiometry

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Abstract: We report the use of Heat transfer Module of COMSOL multiphysics and a technique based on Infrared Photothermal Radiometry to study the heat transfer of a homogeneous and isotropic solid material excited by a periodic laser beam on the front side of the sample, and an infrared detector on the rear side in order to obtain the evolution of the temperature difference with the exposure time. Also, we compared the experimental with the simulated results obtaining a good agree between them.

Keywords: Heat Transfer, infrared radiometry

1. Introduction

Development and applications of heat transfer is of fundamental importance in many branches of engineering since provides economical and efficient solutions for critical problems encountered in many engineering items of equipment [1, 2].

Photothermal (PT) techniques are a high sensitivity methods used to investigate the thermal properties of a variety of materials. Progress in the PT sciences has been made mainly due to continued improvements in the development of light sources and equipment for data collection and processing [3-5]. In particular, photothermal radiometry (PTR) originally proposed by Nordal and Kanstad [6] is one of the most important techniques because its detection method involves nondestructive, noncontact remote sensing. This technique consists of impinging a modulated light beam onto the sample and the resulting heat flux produces a periodic temperature distribution, called “thermal wave”. As a result, infrared (IR) Planck radiation is emitted and subsequently detected by an IR detector. Since temperature rise depends on the thermal properties of the sample, modulated PTR can be used to investigate thermal response of materials [7–8].

Many times, the complexity of the mathematical problem proposed to describe the experimental conditions in the measurements is very complex and only possible to obtain a mathematical model based in an analytical solution with several approximations that not reflect the physical reality of the problem. Fortunately, nowadays the development of the advanced numerical methods and computing systems allow the application of high level software for obtain an approximate solution to a complex mathematical problem with a boundary conditions congruent with the physical reality. In particular, Comsol Multiphysics is a powerful Finite Element (FEM) Partial Differential Equation (PDE) solution engine [9] useful to obtain a numerical solution in complex problems.

In this work, the Comsol Multiphysics software is used to determinate the numerical solution of a periodic temperature distribution in a sample measured by PTR technique with the congruent boundary conditions to the physical reality of the experimental setup. In addition, it realized a comparison between numerical results and experimental ones.

2. Experimental

The PTR system consists of a sample holder fixed to an aluminum rail, the light beam is generated by a Lasever laser, 473-532 nm wavelength and 1W power, with integrated driver to receive TTL signals, a lock-in amplifier with two functions: send the TTL signal to synchronize the shutter driver and capture data. The IR signal is detected with an Exergen smart IR t/c sensor, with integrated scanning system for sending data port RS-232 and it was implemented a LabView software for automation and experimental data acquisition.

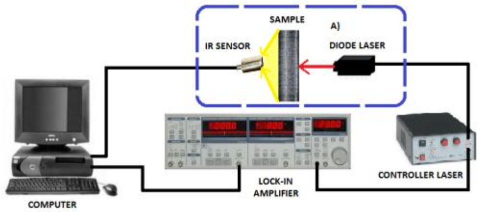

Figure 1. Experimental setup of the Infrared Photothermal Radiometry system

It was considered a crystalline silicon sample of 400 μm thickness. The laser beam impinges on the sample front face in an area of 15 mm^2, which was covered with a thin layer of painting graphite to prevent the laser beam reflection. The sample was heated in an interval of 600 seconds and the temperature rise was measured on the sample rear face. There works at different frequencies in the range 0.01Hz to 1Hz, in order of obtain the temperature oscillations, which correspond to the frequency assigned in the Lock-in. Figure 5(a) shows the experimental results of the temperature increase versus time at a frequency of 0.1 hz and the black curve in figure 6 shows the corresponding for a frequency of 0.01 hz.

3. Use of COMSOL Multiphysics

The heat transfer analysis was carried out on the front side of the sample, the temperature profile was obtained at a frequency of the incident laser beam of 0.01-1Hz, at different times. It was obtained the temperature distribution in the sample as a function of time by means of the solution of the heat diffusion equation with the corresponding boundary conditions:

$$-\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\dot{q}=\rho c\frac{\partial T}{\partial \tau} \tag{1}$$

$$\Delta T\big|_{x=0}=T_i\left[1+\cos(2\pi ft+\pi)\right] \tag{2}$$

$$-k_s\Delta T\big|_{x=L}=-k_a\Delta T\big|_{x=L} \tag{3}$$

Here, f is the modulation frequency of the incident beam, L is the sample thickness, k_s is the thermal conductivity of the sample, k_a is the thermal conductivity of the air, ρ is the density, c is the specific heat and q is the rate of heat.

The models were developed under version 4.1 and then worked under version 4.2. The physics used in COMSOL was heat transfer, the interface provides the equations, boundary conditions and sources for modeling. We used the default physical model heat transfer in solids. The geometry was designed in COMSOL by using composite objects and blocks, see Fig 2. The equations were defined as variables under global definitions. In the heat transfer model we doesn't use the material library. Instead, all necessary values like effective heat capacity, heat conductivity and specific density were described as parameters in all cases, see appendix. All simulations were performed with a 3D model. We used a Tetrahedral mesh with a minimum of 7 elements, Fig 3.

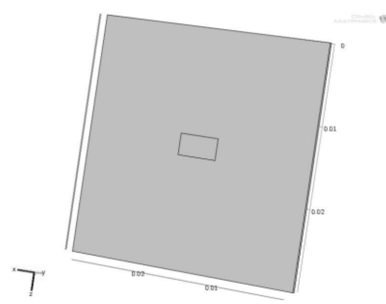

Figure 2. 3D model of the sample

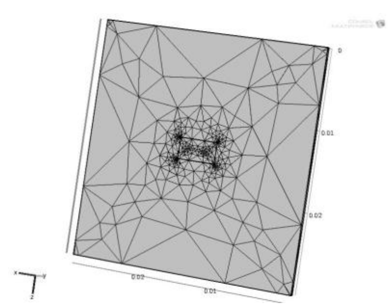

Figure 3. Meshing used in the simulation process.

4. Results and Discussion

Figure 4 show the temperature distribution on the front side of the sample at 0.1 Hz of the modulation frequency, and considering three cases in the exposure time, 10s, 50s and 80s.

a)

b)

c)

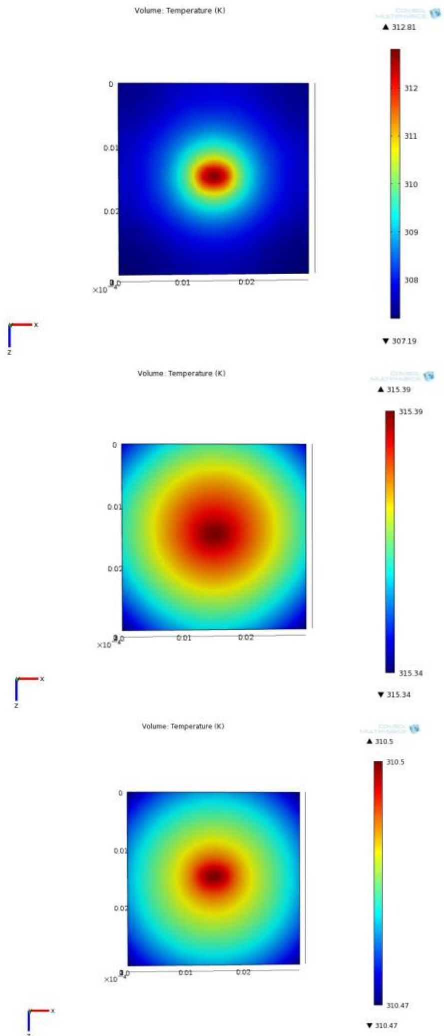

Figure 4. Temperature distribution on the front side of the sample at a modulation frequency of 0.1 Hz. a) 10s b) 50s and c) 80s of exposure time.

Figure 5 shows the temperature evolution at the front face of the sample in an exposure time of 600s and frequency of 0.1 Hz. Graph 5(a) shows the experimental curve, and graph 5(b) the simulated result. From the comparison between these graphs it was obtained a similar behavior in the amplitude and in the shape of the curves too, which demonstrate a very good agree between these results.

In addition, figure 6 shows a comparison between the experimental and simulated results for a modulated frequency of 0.01 Hz and an exposure time of 500s. This figure show a significant correspondence between experimental and simulates results, in particular for exposure times below 300s and with a difference that increases t higher exposure times.

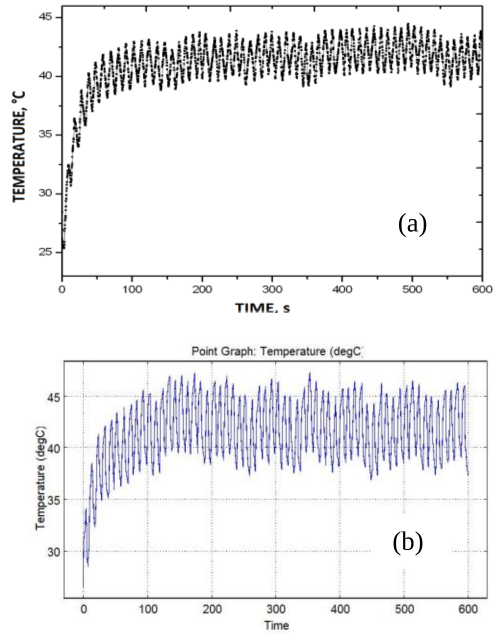

Figure 5. Temperature evolution at the front face of the sample in a time exposure of 600s and frequency of 0.1 Hz. (a) Experimental and (b) Simulated results.

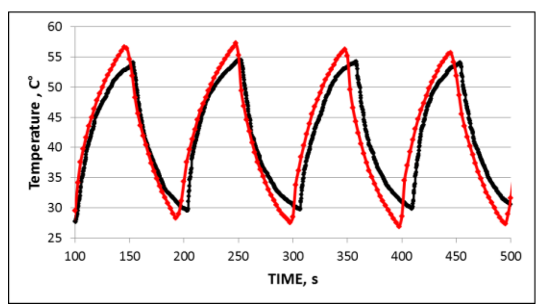

Figure 6. Comparison of the experimental (black points) and simulated (circle points) results for modulation frequency of 0.01 Hz.

5. Conclusions

By means of the application of the Comsol Multiphysics software it was obtained the numerical solution of the periodic temperature distribution in a sample measured by the configuration of PTR technique with the congruent boundary conditions to the physical reality of the experimental setup. The good agree between the experimental and the simulated results, show the utility of the Comsol software in the simulation process of Heat Transfer in solids in infrared PTR measurements.

6. References

1. Terry M. Tritt, Thermal Conductivity, theory properties and applications, *Springer* (2004)
2. Roland W. Lewis, Perumal Nithiarasu, Kankanhally N. Seetharamu, Fundamentals of the finite element method for heat and fluid flow, *Willey* (2008)
3. H. Vargas, L. C. M. Miranda, Photoacoustic measurement of thermal diffusivity of polymer foils *Phys. Rep*. **161**, 43 (1988).
4. D. Almond and P. Patel, Photothermal Science and Techniques, *Chapman and Hall, London* (1996)
5. A. C. Tam, Applications of photoacoustic sensing techniques, *Rev. Mod. Phys*. **58**, 381 (1986).
6. E. Nordal and S. O. Kanstad, Photothermal Radiometry, *Phys. Scr*. **20**, 659 (1979)
7. S. Andre, B. Remy, D. Maillet, and A. Degiovanni, J, Modulated photothermal radiometry applied to semitransparent samples: Models and experiments. *Appl. Phys*. **96**, 2566 (2004).
8. M. Depriester, P. Hus, S. Delenclos, and H. Sahraoui, Rev. Sci. Instrum. **76**, 074902 (2005).
9. R. Pryor W, Multiphysics Modeling using Comsol 4 A First Principles Approach, *Mercury Learning and Information*. (2012)

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8. Appendix

Table 1: Boundary Conditions and material properties

Variable	Value	Units
Material	Silicon solid	
Width block 1	0.03	M
Depth block1	0.0004	M
Height block 1	0.03	M
Width block 2	0.005	M
Depth block 2	0.0001	M
Height block 2	0.00267	M
Ambient temperature	293.15	K
Watts	7100	W/m^2
Heat capacity	794	J/(kg*K)
Density	2330	kg/m^3
Thermal conductivity	148	W/(m*K)