8^{th} GRACM International Congress on Computational Mechanics
Volos, 12 July – 15 July 2015

A FEM STUDY ON THE INFLUENCE OF THE GEOMETRIC CHARACTERISTICS OF METALLIC FILMS IRRADIATED BY NANOSECOND LASER PULSES

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Keywords: Finite Element Method – FEM, Laser-Matter Interactions, Metallic films, matter defects.

Abstract. *The dynamic mechanical behavior of metallic film-substrate systems excited by a nanosecond laser pulse is studied in the thermoelastic, non-destructive, regime. In this regime, the deformation of the metallic film occurs after laser excitation without altering its elastic properties. The absorption of the laser pulse results in an increased localized temperature, which in turn causes thermal expansion and generates acoustic waves that propagate the solid target. Matter's dynamic response is numerically described by a coupled thermal-structural, transient, three-dimensional (3D) Finite Element (FE) model. The 3D-FE model has been validated by the help of experimental results obtained by the help of laser interferometric methods. The influence of the geometric characteristics of the metal films to the generation and propagation of the acoustic waves and to their mechanical properties are studied in this paper. The influence of the thickness of the metal film in relation to the displacement and the temperature distributions is investigated. Moreover, an initial approach to the understanding of the mechanical behavior of matter in the case of presence of geometrical defects like gaps, holes or bubbles is also attempted. Mechanical features like displacements, velocities, temperatures, stresses and strains are analyzed in the transient time and space solution domains.*

1 INTRODUCTION

Various approaches in literature are modeling the generation and propagation of ultrasounds in solids, having cracks or defects, by the help of numerical simulations. In the most of the approaches, surface fatigue cracks are replaced by the surface notch of rectangular shape for the convenience of modeling [1,2]. This modeling approximation is adopted in this research work. Since the existence of defects in matter create complicated geometries and sharpened edges, a flexible and versatile numerical method has to be selected, in order to correctly describe the solution domain and capture the rapid changes of the occurring stress and strain results, when the desired precision varies over the entire domain or/and when the solution lacks of smoothness. These features are the basic characteristics of the Finite Element Method (FEM) that may also provide insights to important mechanical features like displacements, velocities, temperatures, stresses and strains in the transient time and space solution domains. Non-destructive testing is essential to monitor areas or volumes that enclose, or not, defects and to evaluate the defects' locations, sizes and characteristics before they become critical [3].

The development of materials and their properties characterization as well as their production processes require new means for the testing monitoring and optimization of their properties. Volume and/or surface breaking cracks and discontinuities are a major problem especially in production and manufacturing [3,4]. Elastic and acoustic waves provide an essential observation method for non-destructive testing by using e.g. acoustic emission, ultrasonics, and acousto-ultrasonics [5]. Laser generated ultrasounds, include a large component of surface wave motion and are therefore particularly useful for the detection of surface defects [2]. Rayleigh waves are surface acoustic waves, commonly referred as SAWs, composed of coupled longitudinal and shear waves, which have been extensively used for surface defect evaluation [6]. The depth of the sample to which a Rayleigh wave penetrates is wavelength dependent, with the amplitude of the wave falling off approximately exponentially with depth.

A method combining experimental study and 3D FEM modeling, previously established and validated in [7-9] has been already used for the monitoring of generation and propagation of SAW waves in thermoelastic, melting and ablation regimes, when thin films are excited by nanosecond laser pulses. This method is here used for non-destructive testing, limiting laser fluences in the thermoelastic regime. The generation and propagation of Rayleigh surface acoustic waves on metallic films is analyzed for various film thicknesses and specifically for 0.5, 0.6, 0.9 and 1.2 μm. Furthermore, four representative test cases of gold film sample over glass with different defects are investigated. In the first test case is modeled a gap defect with an open geometry reaching the bottom of the gold film's depth, while in the second test case the same defect with a closed geometry is modeled. In the third test case a gap with an open geometry is extended to full depth, reaching the bottom of the sample, while in the fourth case a gap with a closed geometry is extended to the half depth of the glass substrate.

2 FINITE ELEMENT MODELING

The heat conduction and wave propagation equation are solved in order to describe the thermal and structural behavior of matter simultaneously, by the help of the 3D FEA model, providing a detailed analysis of the equations parameters [7-9]. The heat conduction equation predicts the induced temperature distribution imposed by the laser energy deposition, while the wave equation determines the displacements of the target. The energy source Q (energy per volume unit per time) is essentially the absorbed energy per unit volume per unit time and is described by the spatiotemporal Gaussian distribution described in Eq. 1.

$$Q(x,y,z,t) = I_0(1-R)e^{-4\ln 2(t/t_0)^2} e^{-(x^2+y^2 / r_0^2)} a_b e^{-a_b z} \tag{1}$$

I_0 is the incident laser intensity on target, R is the optical reflectivity of the sample, α_b is the optical absorption coefficient, t_0 is the laser pulse duration at full-width at half-maximum (FWHM) and r_0 is the FWHM laser beam radius on the target corresponding to the laser spot. The model consists of a thin gold metal film having a thickness of 0.6 micrometers, and is supported on a thick glass substrate of 200 micron thickness.

In Fig. 1, the geometry and discretization of the 3D quarter symmetry model along with the orientation of the defect for the examined test cases is presented. Thickness variation detail of the examined test cases with no defect is also shown in the same figure. At the left corner of figure 1, the open geometry gap defect is depicted while the volume gap defect reaching the substrate's bottom is shown at the right of the same figure. The defect has a length of 20 μm and a width of 1 μm, with the height varying according to the examined test case. Due to the high frequencies of the laser generated SAWs as well as the need for transient analysis, a small element size is necessary. The Lagrangian mesh is locally adaptive according to the simulation needs. Symmetric loads and boundary conditions are considered and the heat generation function Q, as described in Eq. (1), is applied on the film body.

3 FEM RESULTS

The proposed 3D FEM model is used to simulate four film-substrate geometries, without a defect. In each of the four test cases, the thickness of the gold thin film varies from 0.5 to 0.6, 0.9 and 1.2 μm, while the thickness of glass remains constant, as presented at the top left detail of Fig. 1.

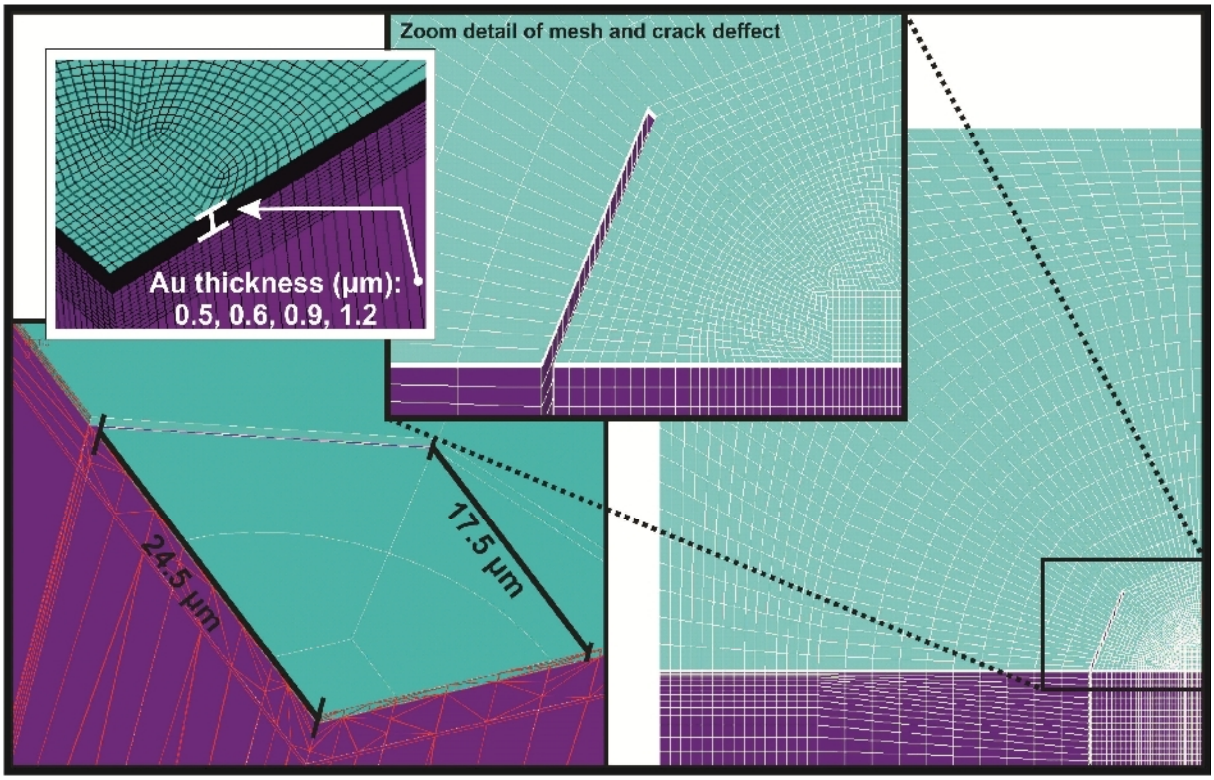

Figure 1. 3D FEM models: geometry and discretization details along with gap defect and it’s orientation. First test case (left – gap defect reaching the bottom of gold film) and third test case (right – volume gap defect) with a zoom detail. The thickness variation detail of test cases of 0.5, 0.6, 0.9 and 1.2 μm is also shown.

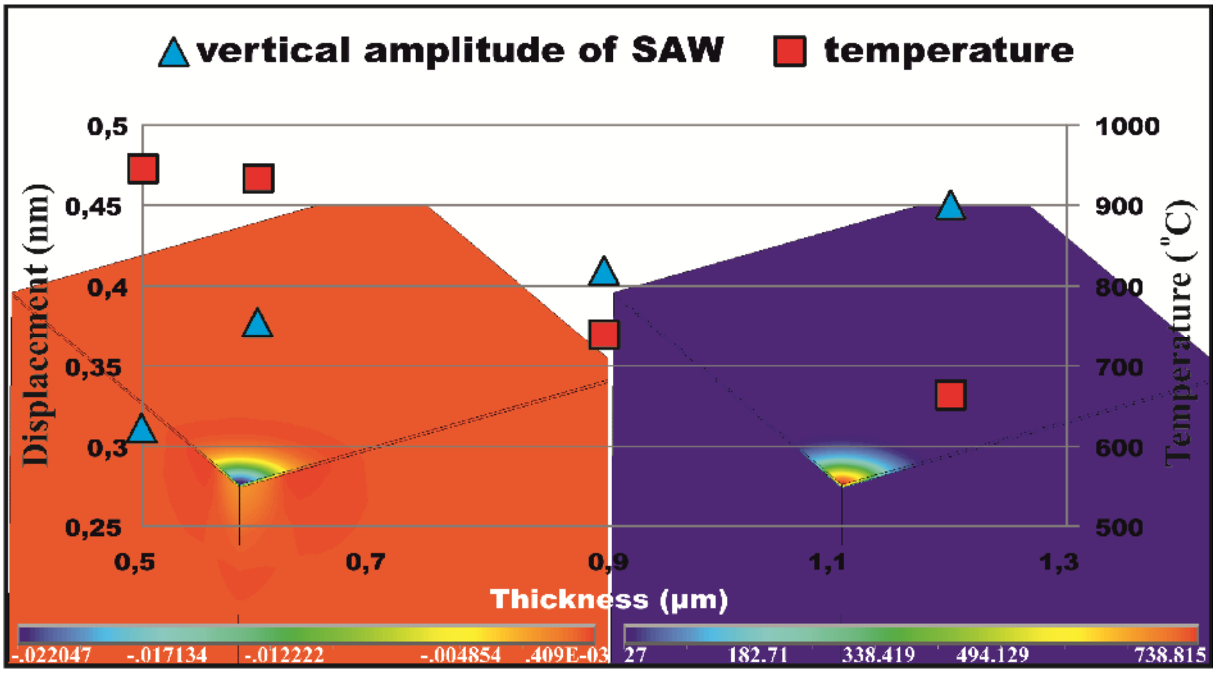

Figure 2. Graph of maximum temperature and vertical amplitude of displacement in relation to thickness along with contours of vertical displacement and temperature 16 ns after irradiation for film-substrate sample with film thickness of 0.9 μm

In Fig. 2 is presented the graph of maximum temperature and maximum vertical amplitude of displacement of the SAW in relation to film thickness for laser fluence of 0.2 J/cm^2, which is below the melting threshold of gold [7] and for 16 ns after irradiation starts, ensuring the thermoelastic response of the metal. Moreover, the contours of vertical displacement and temperature are also shown, sixteen nanoseconds after irradiation for a film-substrate sample with film thickness of 0.9 μm. From the graph it may be observed that while the thickness of the film increases, the temperature distribution decreases, while the displacement of the SAW increases. As was expected SAWs may be easily detected and monitored in thicker films by experiments.

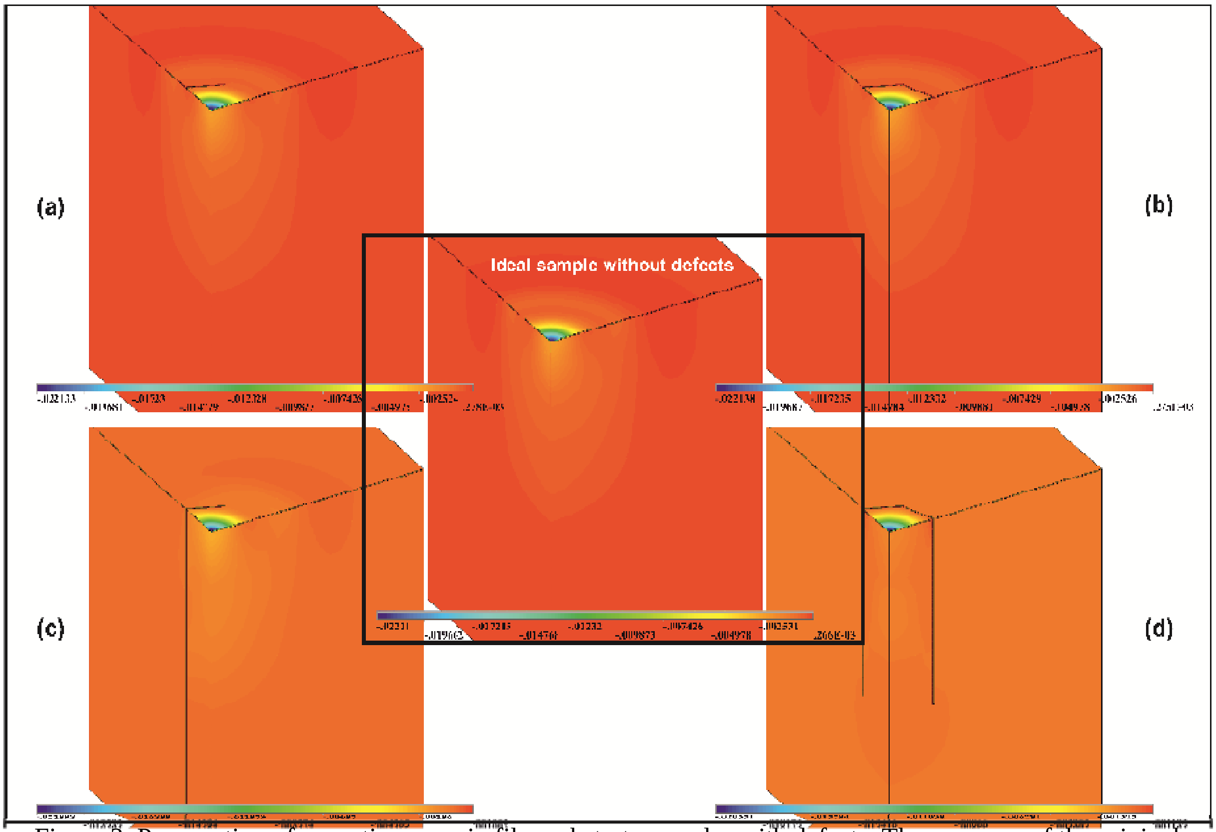

Figure 3. Propagation of acoustic waves in film-substrate samples with defects. The response of the original sample without defects is depicted in the centre of the figure.

Results of vertical displacement are presented in Fig. 3 for model with defects and with no defect. For the first two test cases the gap has a depth of 0.6 μm, reaching the bottom of gold film. As presented in Figure 3(a) and (b), for these two cases FEA results show that the presence of this discontinuity has no influence to the propagation of Rayleigh surface acoustic waves. In the third test case, where the same defect reaches the bottom of the glass (whole volume defect), a part of the Rayleigh surface acoustic waves is transmitted while the rest is reflected as may be noticed in figure 3(b). For the fourth test case, where the surface gap discontinuity has a closed geometry a small part of the of the Rayleigh surface acoustic waves is transmitted (5% of the maximum vertical displacement).

4 CONCLUSIONS

The numerical results indicate that for an irradiated film-substrate with defects reaching the film’s bottom the generation and propagation of SAWs is not affected. Therefore when an obtained experimental result for an irradiated thin film-substrate system indicates an ultrasound, where only a part of it is transmitted, then a defect exists with a depth reaching the substrate. Future simulations and corresponding experiments will be performed for the study of the influence of depth, width and length and of various types of defects, in relation to the propagation of SAWs.

ACKNOWLEDGMENTS

The authors acknowledge financial support through the Action “National Research Infrastructure for HiPER” MIS 376841 (co-funded by the European Union and Hellenic National funds within the Operational Programme “Competitiveness and Entrepreneurship”).

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