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Metallography Investigation of Thermal Wave Control by Magneto-Static Field

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Abstract: In this paper we have studied the effect of magneto-static field on propagation of thermal wave generated in metal by pulsed laser. In fact this interaction generate acoustic wave in different mechanisms. However, always the common mechanism in the interactions of laser pulse and metal is the thermo-elastic wave generation. Applying the suitable magneto-static field on the surface of interaction of laser pulse and metal can trap the propagation of thermal wave in thermo-elastic regime. The physical mechanism of trapping and experimental results have investigated in this paper. We obtained maximum reduction in 2D thermal wave propagation around $18 \pm 1\%$ in simulation and around 5.3% by metallography.

Keywords: Thermal Wave, Metallography, Magnetic Field.

1. INTRODUCTION

For the first time, the interaction of laser and matter for generation of thermo-elastic pulse investigated by Kruezer (1971) [1]. Advance in laser science and technology in generation of ultrashort and high power pulse opens an interesting field for researchers to investigate and find methods for generation of short and ultrashort acoustic waves [2]. Different mechanism have studied in the interaction of laser and different matters such as metals, semiconductors and liquids for generation of thermos-elastic wave and elastic waves through ablation regime [2-10]. Thermo-elastic regime and ablation regime are two main category of interaction [4, 5]. A good review for thermo-elastic regime can find in [6]. For interaction of low frequency laser with matter, the review of Tam is interesting [7]. In ablation regime Gusev *et.al.* have comprehensive reviews and works [8,9]. Two reference books for interest researchers are [4, 5]. The propagation of thermo-elastic wave in mater have a key role in laser metal welding and sensory materials and have massive weight in literatures as well as another interesting branch of laser and matter interaction [10]. In addition some

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new studies on nanoparticles substrates and metamaterial interactions to the laser beam have been investigated by some researchers [12,13] which can leads to new regimes of sound generation by laser.
Almost the common mechanism in all interactions is thermo-elastic mechanism. The more absorption of laser pulse by matter, the more efficiency of mechanism. But the higher energy of laser pulse and the higher absorption may damage the target and the modification on the surface of target may cause different conditions for interaction of laser pulse and matter. The presence of magnetic field normal to the surface of metal can inhibit the thermo-elastic wave propagation.
In the section 2 we will construct the system of equation of motion of electrons as main carrier of thermo-elastic wave in metals after decaying of lattice vibration. In section 3 the equations will solve numerically and we will discuss the results. In the fourth section an experimental result will offer to confirm the simulation.

2. CONSTRUCTION OF SYSTEM OF EQUATION OF MOTION OF ELECTRONS

According to Righi-Lecuc effect [11], the main part of thermal wave propagation in metals is carried by electrons. In fact thermo-elastic wave generated by laser propagate through conductance electrons and the lattice contribution is negligible after small distance from source [4]. In fact the propagation through conductance electrons is dominant after decay of lattice vibration and thermal wave will continue through conductance electrons. In higher laser power the contribution of lattice in acoustic wave generation will be reasonable [5]. Although unreal, but we insert the shape of acoustic wave as a sine wave. As we will see in last section, deviation from sine wave have little effect in our simulation. Conductance electrons have assumed free electrons and the Coulomb force exist between them. So the system of equation of motion in presence of sine thermo-elastic wave is:

$$\begin{cases} \dfrac{d^2 x_i}{dt^2} = \dfrac{1}{m_e}\left(\dfrac{e^2}{4\pi\varepsilon_0}\displaystyle\sum_{j(\neq i)=1}^{N}\dfrac{(x_i - x_j)}{\left((x_i - x_j)^2 + (y_i - y_j)^2\right)^{3/2}}\right) + \dfrac{F_{0x}}{m_e}\sin(\omega t) \\ \dfrac{d^2 y_i}{dt^2} = \dfrac{1}{m_e}\left(\dfrac{e^2}{4\pi\varepsilon_0}\displaystyle\sum_{j(\neq i)=1}^{N}\dfrac{(y_i - y_j)}{\left((x_i - x_j)^2 + (y_i - y_j)^2\right)^{3/2}}\right) + \dfrac{F_{0y}}{m_e}\sin(\omega t) \end{cases}, i = 1 \cdots N \quad (1)$$

Where x and y are the components of electrons position on surface, m_e is the electron mass, e is electron electric charge, F_{0x} and F_{0y} are the components of force exerted to electrons due to acoustic pulse and ω is the frequency of acoustic wave.

Because of random motion of conductance electrons in metal, the initial values for $x_{i=1,\cdots N}$ and $y_{i=1,\cdots N}$ have chosen randomly. The initial values for velocity components $\frac{dx_{i=1,\cdots N}}{dt}$ and $\frac{dy_{i=1,\cdots N}}{dt}$ have chosen randomly from Gaussian distribution of electron speeds at temperature T with the peak value, $v_{peak} = \sqrt{\frac{3K_B T}{m_e}}$.

System of equations (1) describe the motion of electrons under influence of thermo-elastic wave with the wavelength $\lambda = \frac{2\pi V_a}{\omega}$ and the amplitude $A = \frac{F_0}{m_e \omega^2}$.

Under influence of static magnetic field B normal to $x - y$ plane, the system of equations (1) will modify to:

$$\begin{cases} \dfrac{d^2 x_i}{dt^2} = \cdots + \dfrac{e}{m_e}\dfrac{dy_i}{dt}B_z \\ \dfrac{d^2 y_i}{dt^2} = \cdots - \dfrac{e}{m_e}\dfrac{dx_i}{dt}B_z \end{cases} ,i = 1 \cdots N \qquad (2)$$

Where " $\cdots$ " denotes the relevant part in the right hand side of equation (1). According to the Maggi-Righi-Leduc effect [11], exerting a magnetic field can reduce thermal conductivity. In practice the presence of suitable magnetic field can somewhat overcome the propagation of thermal wave generated by thermo-elastic mechanism.

In the next section we will solve general form of equation (2) and will investigate some special cases.

3. SIMULATION OF THERMO-ELASTIC WAVE PROPAGATION IN METAL

For study equation (2) we have consider a sine wave with amplitude “a” and frequency “ω” propagating through an Aluminum sheet as longitude wave. To close to problem assume that electrons have no initial speed and all are at rest. Generation of longitude ultrasonic wave through electrons lead to sine motion of electrons. Consider some electrons within the sea of conductance electrons. Effect of normal B field reduce the course of electron motion and change the straight line of motion under sine wave, see figure (1).

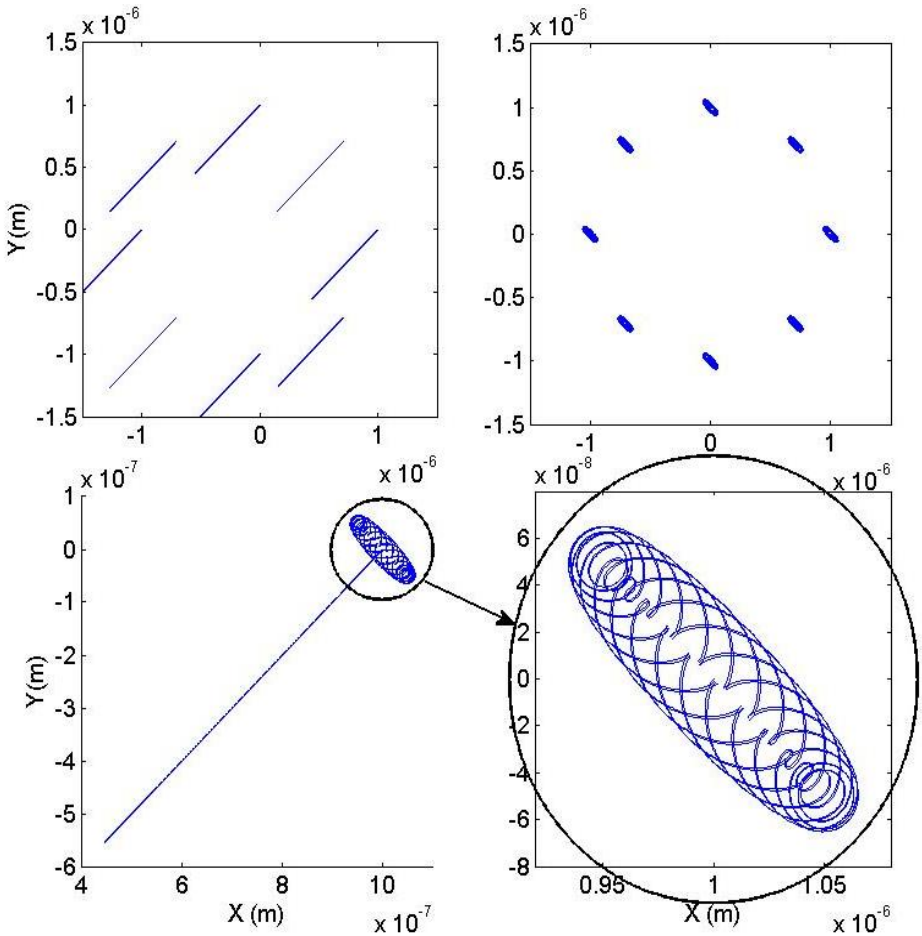

Fig. 1. (top-left), Sample of electrons, just under influence of sine wave, (top-right) motion of electrons both under influence of sine wave and suitable normal magnetic field. (bottom-left), zoom on a single electron, this diagram compares amplitude and direction of motion with and without presence of magnetic field. (bottom-right), close view to motion under B field.

But this is not the all of story. Electrons have thermal speed in the order of hundred kilometer per second at room temperature and we don't considered the Coulomb force yet. The effect of electric and magnetic force in addition to sine wave and Gaussian distribution of thermal speed cause a complicated motion of electrons, for example see figure (2).

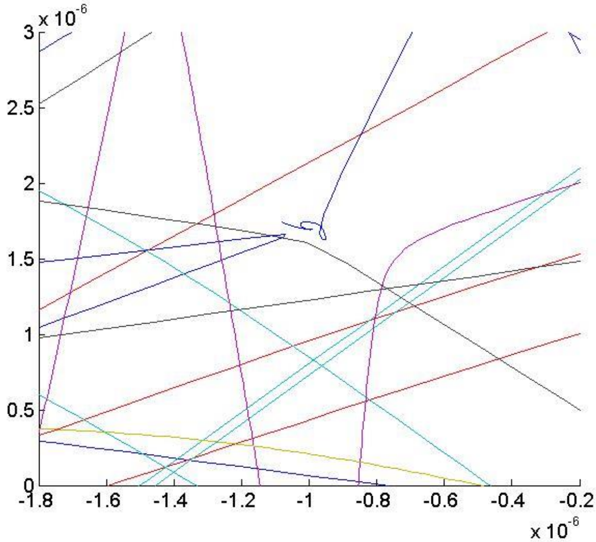

Fig. 2. Complicated electrons motion under influence of magnetic field, thermo-elastic wave, Coulomb force and thermal speed.

For simplicity we consider a small portion of 2d sheet of aluminum with free boundary. We set a circle around the point source of longitude acoustic wave. For considering the effect of magnetic field on the motion of electrons, we have counted the times of entrance plus exit of electrons through circle, see figure (3).

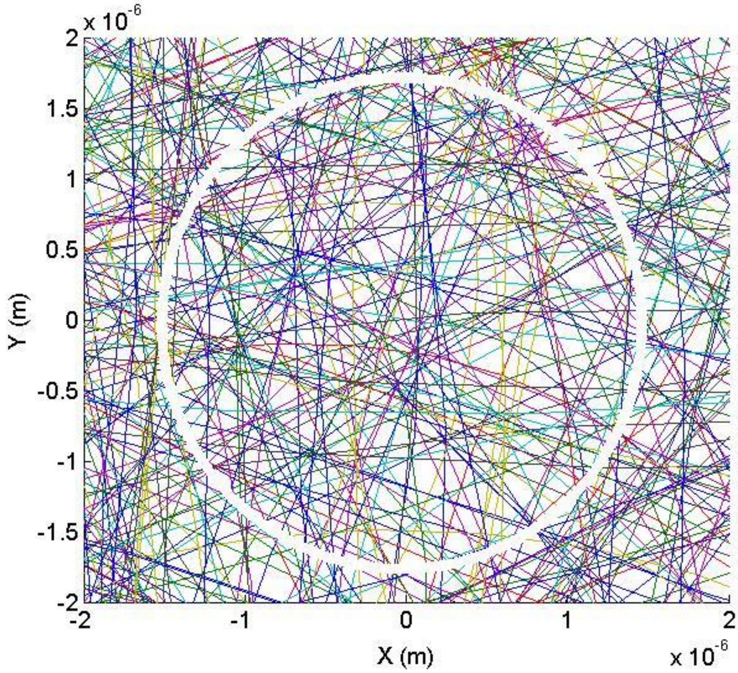

Fig. 3. We put a circle within the path of electrons and have counted entrance plus exit of electrons through circle in time interval "t", 1- under influence of magnetic field, $M'(B)$ and 2- without magnetic field, M.

Considering $N = (\text{Avogadro's number})^{2/3}$ electrons in a surface of cube include 1 mole material. Regarding the performance of our computer, we simulate the motion of conductance electrons in $16\ \mu m^2$ for aluminum. We have simulated the motion of this large set of electrons ($n \sim 10^7$), with and without presence of B field under the influence of thermo-elastic wave. We have counted the number of times of entrance plus exit of electrons through circle without effect of B field (M) and in presence of B field ($M'(B)$). In fact the parameter ($\frac{M'(B)}{M}$) denotes the amount of influence of B field on propagation of thermal wave, see figure (4). As we expected before, increasing the B field cause the reduction of radial motion. Because of random initial speed of electrons in different simulations we had different values for ($\frac{M'(B)}{M}$) and we depict this by error bar, see figure (4).

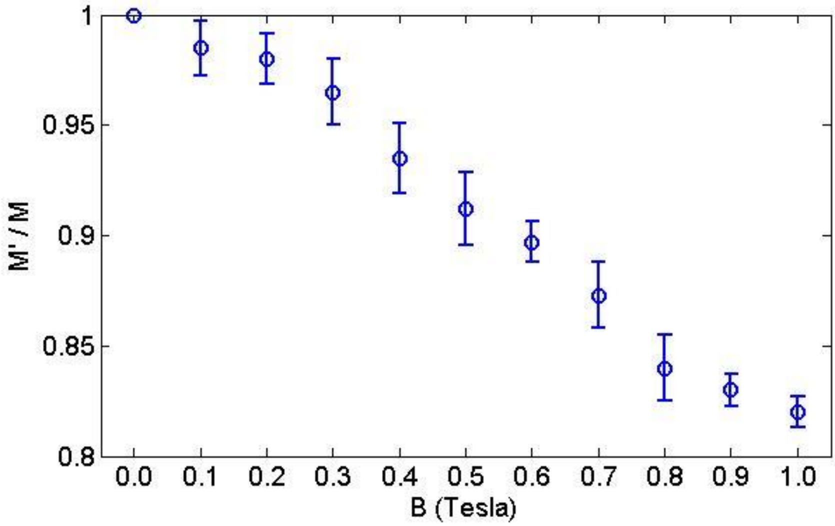

Fig. 4. The value of $\frac{M'(B)}{M}$ decreases with magnetic field increasing normal to the surface of thermal wave propagation.

4. EXPERIMENTAL OBSERVATION AND DISCUSSION

For study the effect of magnetic field on thermal wave expansion, we used the effect of presence of magnetic field on melting area of aluminum, under the irradiation of high power pulsed laser. Taking microscopic photo from the cross section of metal at middle line of laser spot, i.e. *metallography*, we saw reduction of melting area under effect of 1.0T magnetic field, right at the location of laser spot on metal (figure 5a.), with respect to absence of magnetic field (5b.). Although melting of metal denotes an ablation regime of interaction, but those part of thermal expansion by conductance electrons leads to reduction of melting area under effect of strong magnetic field. This reduction was around 5.3%. It seems that the applying strong magnetic field on metals can help metal welding. In some of metals like aluminum, high thermal conductivity inhibit the concentration of heat for melting and metal welding.

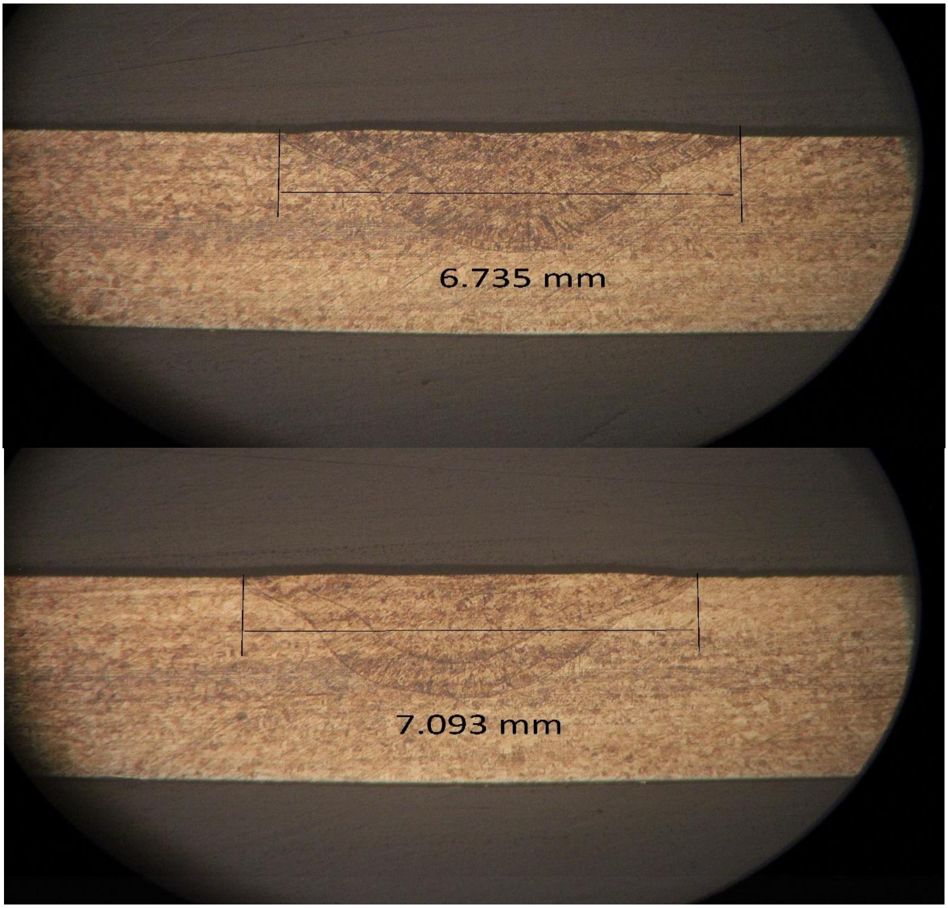

Fig. 5. a: top photo depicts the effect of laser pulse on aluminum in presence of 1.0T normal magnetic field. b: bottom photo depicts the effect of laser pulse in absence of magnetic field; all other conditions are same as test of figure a.

5- CONCLUSION

In this paper we have studied the effect of magnetic field both theoretically and experimentally. Simulation showed that the presence of magnetic field can reduce radial propagation of thermal wave. In metallography we saw this effect by reduction of melting area of aluminum under irradiation of pulsed laser. We have done same simulation for Gaussian wave with width equal to sine wave amplitude and same frequency of repetition. It seems that the shape of wave have no reasonable effect on simulation, but the results are sensitive to frequency of acoustic wave. In fact our simulation shows that increasing the frequency from 1 GHz to 1 THz cause the value of ($\frac{M'(B)}{M}$) reduce by more than 90% in constant magnetic field. The reason seems to be the closing of electrons speed under influence of wave to random thermal speed at room temperature. On the other hand the amplitude of electron motion under THz thermal wave reduce to sub-mean free path distance.

REFERENCES

[1] L. B. Kreuzer, *Ultra low gas concentration Infrared absorption spectroscopy*, J. APP. Phys. 42 (1971) 2934.

[2] J. W. Wagner, *Laser Sources For Generation of Ultrasound*, Contract No. NAG-1-1524, NASA, CR, (2008) 93-102.

[3] S. A. Akhmanov and V. E. Gusev, *Laser excitation of ultrashort acoustic pulses*, Sov. Phys. Usp. (1992), 135-153,

[4] C.B. Scruby and L. E. Drain, *Laser ultrasonic, Laser and applications*, Ed. Adam Hilger, 1990.

[5] V. E. Gusev, *Laser optoacoustics*, Ed. AIP, 1993.

[6] P. Ruello, V. E. Gusev ,*Physical mechanisms of coherent acoustic phonons generation by ultrafast laser action*, ScienceDirect, Ultrasonics 56 (2015), 21–35.

[7] A.C. Tam, *Applications of photoacoustic sensing techniques*, Rev. Mod. Phys. 58 (1986) 381–431.

[8] V. E. Gusev, A. Karabutov, *Laser Optoacoustics*, AIP, New York (1993) 512-523.

[9] S.A. Akhmanov, V.E. Gusev, *Thermal effect on sound generation by laser*, Sov. Phys. Usp. (1992) 171- 176.

[10] T. Kundu , *Ultrasonic non-destructive evaluation,* Ed. CRC Press, 2003.

[11] D. Cleary, J. N. Lalena, *Principle of inorganic material design*, Ed. John Wiley and sons, 2010.

[12] M. Servatkhah, S. Goodarzi, *Interaction of Laser Beam and Gold Nanoparticles, Study of Scattering Intensity and the Effective Parameters*, Journal of Optoelectronical Nanostructures 2 (2017), 3.

[13] M. Servatkhah, H. Alaei, *The Effect of Antenna Movement and Material Properties on Electromagnetically Induced Transparency*

in a Two- Dimensional Metamaterials, Journal of Optoelectronical Nanostructures 1 (2016), 2.