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DETERMINATION SOUND SPEED OF METAL IN AQUEOUS SOLUTION VIA LASER INDUCED ACOUSTIC WAVE TECHNIQUE

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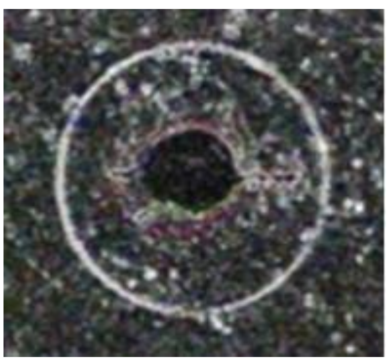
Graphical abstract



Abstract

Laser induced breakdown and shock wave propagation are nonlinear phenomena. The high temperature and high pressure associated with plasma formation offering a lot advantages in industrial and scientific research. However not many realized that the end product of nonlinear effect such as the generation of acoustic wave will also attribute to significant impact. Thus the intention of this study is to materialize the usefulness of such acoustic wave for determination the sound speed of metal element like Pb, Hg and K in aqueous solution. In this attempt a Q-switched Nd:YAG laser was focused to induce optical breakdown and its associated shock wave generation which later follow by the generation of acoustic wave. The phenomenon is observed in conjunction with high speed photography based shadowgraph technique. The experimental results of sound speed for K, Hg and Pb is found in good agreement with the standard value from references. This confirmed that laser induced acoustic wave will be other alternative method for measuring sound speed for metal element in periodic table.

Keywords: Nd:YAG laser, shock wave, acoustic wave, metal element, aqueous solution, breakdown, plasma

Abstrak

Laser pecahan teraruh dan perambatan gelombang kejutan adalah fenomena tidak linear. Suhu tinggi dan tekanan tinggi yang dikaitkan dengan pembentukan plasma menawarkan banyak kelebihan dalam penyelidikan industri dan saintifik. Walau bagaimanapun tidak ramai menyedari bahawa kesan tak linear seperti penjanaan gelombang akustik boleh memberikan impak dalam sesuatu aplikasi. Tujuan kajian ini adalah untuk menunjukkan salah satu kegunaan gelombang akustik iaitu bagi penentuan kelajuan bunyi unsur logam seperti Pb, Hg dan K dalam air. Dalam usaha ini laser Nd:YAG suis-Q ditumpukan untuk mewujudkan cahaya pecahan teraruh dan menghasilkan gelombang kejutan serta diikuti dengan penjanaan gelombang akustik. Fenomena ini dapat dilihat dengan menggunakan teknik fotografi berkelajuan tinggi. Keputusan kajian menunjukkan kelajuan bunyi untuk K, Hg dan Pb menghampiri nilai standard. Justeru itu, ini mengesahkan bahawa gelombang akustik yang dihasilkan oleh laser boleh menjadi kaedah alternatif bagi mengukur kelajuan bunyi untuk unsur logam dalam jadual berkala.

Kata kunci: Laser Nd: YAG, gelombang kejutan; gelombang akustik, larutan unsur logam, plasma

1.0 INTRODUCTION

Focusing intense pulse laser in the medium can cause optical breakdown and nonlinear effects. Among the common phenomena involve are plasma formation and shock wave propagation. Such event can occur in solids [1], [2], liquids [3], [4], [5], and gases [6]. The breakdown generates plasma with high temperature in the range of11000 K and contains high population of ion charges. Meanwhile shock wave induces high pressure since it is propagates with supersonic in the earlier stage and followed by the acoustic sound speed of the medium [7]. The high plasma temperature associated with high pressure of shock wave induced a lot of advantages and that the main mechanism applied in industrial and scientific research. Such nonlinear effects can cause vaporization, chemical reactions, thermo elastic process and electrostriction [8]. These phenomena only can be achieved by using high power laser system that possible to induce breakdown at threshold power density of 10^8 W/cm^2 [3].

Recently, laser-induced breakdown has become a great interest. It has been widely used in material processing like laser surface alloying [9], [10], in detecting hydrocarbon level in water [11], laser induced breakdown spectroscopy in soil [12], [13], [14]. Laser in liquid also used for fabricate and synthesize gold nanoparticle [15], [16], [17], [18]. Although the nonlinear effect of laser breakdown have been widely used, however, the sound induced by the laser breakdown still lack of attention. Hence in this work the phenomenon of sound wave induced by laser breakdown become the intension in this study.

A fundamental study was carried out in conjunction with of high-speed photography system. Several metals in aqueous solutions are employed as the target material, A Q-switched Nd:YAG laser was used to induce optical breakdown. The dynamic acoustic wave propagation was demonstrated and discussed in detail.

2.0 EXPERIMENTAL

Figure 1 shows the schematic diagram of the experimental setup for acoustic wave generation and high-speed photography system. The experiments have been performed with two lasers; a Q-switched neodymium yttrium aluminum garnet (Nd:YAG) and a nitrogen pumped dye laser.

The Nd:YAG laser from Lumonics (model HY200) acts as the main light source to induce optical breakdown. Meanwhile the dye laser was used in the high speed photography system in order to record the shock waves images. The Nd:YAG laser operated in fundamental wavelength of 1064 nm with pulse duration of 10 ns at full width at half-maximum (FWHM). The output energy is kept constant at 47 mJ per pulse and repeated with frequency of 1 Hz. The laser light was focused in a medium by a set of combination lens; initially with a negative lens of -25 mm in order to diverge the beam and converge the beam back with a positive lens of 28 mm. By doing these, a point source was formed in the medium. It is crucial to get the point in attempt to generate a spherical (3D) or circular acoustic wave. Otherwise, if only a single lens is used to focus the light, multiple of different size of breakdowns will occur and subsequently generates different sizes of shock waves [6]. In this work several aqueous metal solutions like Pb, Hg and K have been selected to be the tested medium.

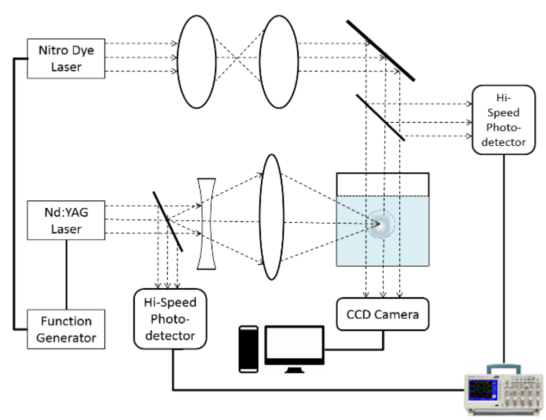


Figure 1 Experimental set-up

3.0 RESULTS AND DISCUSSIONS

The typical results of dynamic acoustic wave propagated in metal (Hg) of aqueous solution nitric acid $HgNO_3$ is presented in Figure 2. In general the shadowgraph comprised of circular waveform (indicate by white). The ring waveform is expanding outward as the time progress. The black dot in the center is the image of plasma. The image is inverted option leading toward opposite color from original. This means the white turn dark color and vice versa. The size of the plasma as well as the ring diameter both are extended as the time pass.

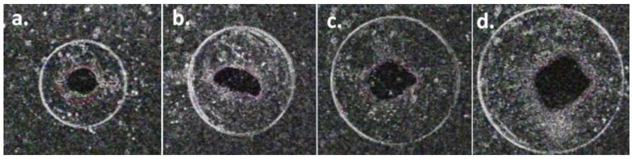


Figure 2 Evolution of acoustic shock wave in mercury nitrate. a. 8.0, b. 8.8, c. 9.6, d. 10.4 μs; (scale = 27.67 pixels/mm)

The pictures in Figure 2. is arranged in the increasing order of time. Each of the pictures is grabbed to frozen the propagation of the acoustic wave in the medium. This accomplished via a single shot in the high-speed photography system. Initially the Nd:YAG laser was triggered to induce optical breakdown. This is followed by plasma formation in the center region associated with shock wave formation. These phenomena occur in the early state within the time lower than 1 μs which is not shown in images. But our concentration is beyond the shock wave propagation. This is determined by the time to frozen the propagation of the wave in the medium. In this study the observation is started beyond 8.0 μs after triggered the Nd:YAG laser. Clearly observed that all the waveforms in the circular ring shape and that is an indicator of acoustic wave formation. As the time progress all the acoustic wave propagate symmetrically outward. As the ring form is bigger than plasma size that illustrated that acoustic wave propagate faster than plasma expansion.

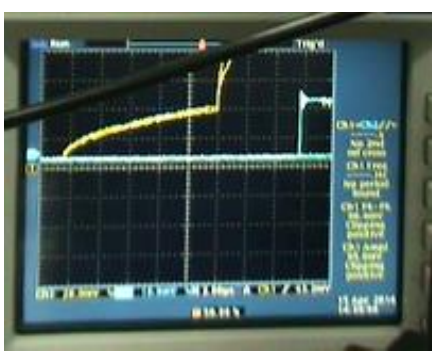


Figure 3 The time delay between the Nd:YAG (yellow) and the nitro-dye laser signals (blue) for aqueous lead in nitric acid (x-axis = 2 μs/div).

During the experiment, the digital oscilloscope as in Figure 3 was used to measure the time delay between the Nd:YAG and nitro-dye laser. In the Figure, the signal was obtained when the laser was induced into the lead nitrate sample. The yellow signal refers to the Nd:YAG while the blue line indicates the nitro-dye signal. The spacing between these two signals is the time delay and closely related with the ring size.

The formation of symmetrically ring shape allows the measurement of diameter of acoustic wave. This analysis is carried out by the aid of ImageJ software. Each frame is gone through editing process to smoothen and sharpen the edge of the ring to be able precisely measured of the diameter. The same procedure is performed for the rest of the picture in each sample liquid under investigation. The results of measurement corresponding to the time are presented in Figure 4. In this Figure, the radius of the acoustic wave which propagated in different metal liquids are plotted with respect to the time of its propagation which measured base on the optical time delay.

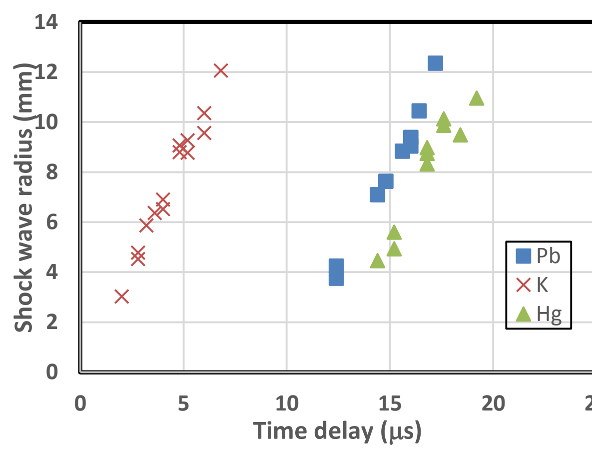


Figure 4 Shock wave radiuses towards time delay

In general the radius of acoustic wave is found linearly increases with the time of propagation. The slope of the linear curve is presented the average of sound speed in each tested liquid. The information extracted from Figure is summarized in Table 1. The sound speed each of the elements are gathered and compared to standard values taken from references. The results obtained from this experiment is quite closed to the standard one. Thus the technique applied for measuring the sound speed of element in this work is validated. The simplicity and the accuracy of the measurements showing the potential of this technique to be used for elemental analysis based on its sound speed.

Table 1 Experimental and standard sound speeds

Sample in nitric acid	Experimental sound speed (m/s)	Standard sound speed (m/s)
Potassium	1777±84	1740[20]
Lead	1618±88	1766[21]
Mercury	1462±164	1449[21]

The different arise in comparison to the standard sound speed is relied on the accuracy of the measurement as well as the stability of the laser performance. There is a possibility for the occurrence of multiple breakdown. In this later case normally involved multiple series of acoustic waves which gives difficulty in measuring the diameter. Therefore, optical alignment in obtaining a single source of acoustic wave is vital task. However taking into account the error in measurement either the time delay or the diameter of the ring waveform, the sound speed estimation is this work still can be accepted.

4.0 CONCLUSION

The nonlinear effect induced by laser breakdown in metal liquid including potassium, lead and mercury have been studied. The formation of spherical wave is an indicator that the acoustic wave is propagated with speed of sound in the media. The average sound speed each of the tested element comprised of K, 1777 ms^{-1}, Hg, 1462 ms^{-1} and Pb, 1618 ms^{-1}. The experimental sound speeds are in good agreement with the references. Thus the laser induced acoustic wave technique is confirmed and potential to be used for elemental analysis.

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