AE monitoring in water during laser shock peening process

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Abstract

Laser shock peening (LSP) is recognized as an efficient surface treatment to improve the fatigue life of metal components. To understand LSP process, acoustic emission (AE) method is expected to be useful for because an elastic wave generates when laser is irradiated on a target. In previous study, we were able to detect shock wave during LSP process by an AE sensor attached to a target and the results show that a cavitation bubble generates after laser irradiation and shock wave is also emitted by the bubble collapse, not only by laser ablation. However, AE wave propagated in a target is affected by the material and size and need to attach an AE sensor to a target directly. Therefore, AE wave propagated in a target has some disadvantage from point of view of AE monitoring. In this study, for easier AE monitoring, we detected AE wave propagated in water and compared that with AE waveforms propagated in a target. Impact forces during LSP process were obtained from detected AE waveforms by deconvolution technique. In addition, at the same time as AE measurement, we observed target surface by high speed camera and investigated phenomena during LSP process.

KEYWORDS: Laser shock peening, Cavitation bubble, Acoustic emission, Inverse analysis

Introduction

Laser shock peening (LSP) technique is surface treatment to improve fatigue property of metals by inducing residual compressive stress to material surface. This technique uses laser to generate the reaction force near material surface by laser ablation and can impact a layer of compressive stress four times deeper than that attainable from conventional shot peening. However, the effect of laser irradiation on materials and phenomenon near laser irradiation point are not well understood yet. The residual stress in depth direction is generally used to evaluate the degree of LSP. Measurement of residual stress can be carried out by both destructive and non-destructive methods. A sample for the first one has to be cut and electrochemically polished while the latter ones provide capability for in-situ evaluation during peening process.

Acoustic emission (AE) method is one of the nondestructive methods to evaluate the size, location and generation time of deformation and damage in real-time. AE method has been successfully applied to laser shot peening method to evaluate peening phenomena and the impact force [1]. In this study, the AE sensors were directly attached on the sample surface, therefore the wave propagation behavior was affected by the geometry and properties of material. In addition, attaching sensor on the sample is not available for process monitoring.

To overcome the problem with sensor attaching, a new approach was proposed in this study. Instead of attaching the sensors on sample surface, several AE sensors were set in the water at fix positions to detect AE propagated though water. This provides the flexibility of specimen setting and allows the capability of on-line process monitoring. The present study is to evaluate the performance of new AE arrangement for monitoring LSP process.

Experimental Methods

• Material

A7075 aluminum alloy, which is used in aerospace field, was used as a sample for this study. The samples were prepared by machining into dimensions of 35x35x20 mm and their surfaces were treated by surface grinding. The sample was then put into the water tank and fixed onto 3D-controllable jig.

• LSP and AE measurement

A schematic diagram of experiment setup is shown in Fig. 1. A Q switched Nd: YAG laser with a wave length of 532 nm, a pulse width of 3-5 ns, and maximum energy of 100 mJ was focused onto the center of the sample surface. At the opposite side of the specimen surface, an AE sensor (Pico, Physical Acoustics Corp.) was attached to detect AE waveforms propagating through the sample. AE waveforms propagating through the water were detected by four sensors located at different (x, y, z) positions as follows: (-50, 7.5, 50), (35, 50, 60), (-15, -50, 70), (50, 0, 50), while (0, 0, 0) position was defined as the center bottom of the tank as shown in Fig. 1(a). The thickness of water layer was kept constant at 30 mm measured from on the top surface of sample. Cables of AE sensors were covered by paste for waterproofing. AE generated during LSP was recorded by Continuous Wave Memory (CWM) system, which is developed by our research group [2]. This system provides a capability to memorize all waveforms continuously at the sampling rate of 10 MHz.

To evaluate the effect of sensor position on detected AE, sensor was set at various distances and angles from the sample as shown in Fig. 1(b). To exclude the effect of water layer on the laser irradiation, the laser was focused onto the sample surface in the horizontal direction. The sensor in water set near sample, in directions of 45° or 75° from the sample. Power density was varied for each sensor position.

In addition, the capability to detect laser-induced breakdown, which is a result from a reaction of laser with confinement layer (water) when the laser energy is very high [4] was carried out. This breakdown causes a generation of cavitation bubble and decrease laser energy on sample surface. The laser-induced breakdowns were intentionally generated by adjusting energy and focus length of the laser in experimental setup shown in Fig. 1(a). Then the thickness of water layer was 10 mm.

• High speed camera observation

A high speed camera (Phantom Miro M310 is a product by Vision Research ® Inc.), which has photograph speed of 220,000 fps and resolutions of 64x64 pixel, was applied to observe sample surface during LSP. Since the times of high speed camera and AE measurement were synchronized, the phenomena detected by high speed camera could be precisely related to detected AE waveforms.

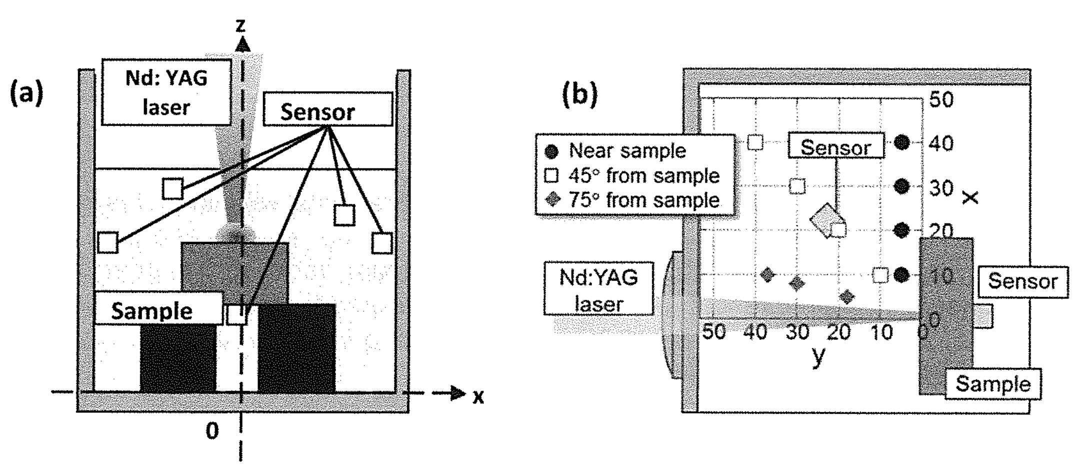

Fig. 1 Schematic diagram of (a) experimental setup 1 and (b) experimental setup 2

• Inverse analysis

Impact force during LSP was evaluated by an inverse analysis of detected AE waveform. Detected AE waveform can be represented following equation,

$$V(t) = S(t) * G(t) * I(t) \quad (1)$$

where $*$ is convolution technique and *V(t), S(t), G(t), I(t)* are detected waveform, response function of sensor, Green's function of sample and source function of impact force, respectively. *S(t)* and *G(t)* could be obtained from a simulation of AE waveform by finite element method and result of sharp pencil lead breaking experiment and then *I(t)* was estimated by the deconvolution technique [3]. AE waveforms were analyzed by this inverse method and obtained impact force values were discussed.

Results and discussion

• *Typical AE waveforms and observation from high speed camera*

Fig. 2 shows examples of AE waveforms detected during LSP from sensors attached on the sample surface and that fixed in the water tank. For each laser irradiation, two AEs could be detected with a time lag of several tens microseconds. According the high speed camera observation, after laser irradiation a bubble generated, expanded its size up to the maximum radius and then became smaller and finally collapsed. Since times of both high speed camera and AE measurement were synchronized, phenomena observed by high speed camera could be correctly related to detected AE waveforms. The sources of the first and latter AEs were laser ablation and bubble collapse, respectively. AE waveforms could be detected from both sensor settings as shown in Fig. 3. A time difference between AE events detected from both sensor generated from discrepancies in propagation length to both sensor, and wave velocity of A7075 and water.

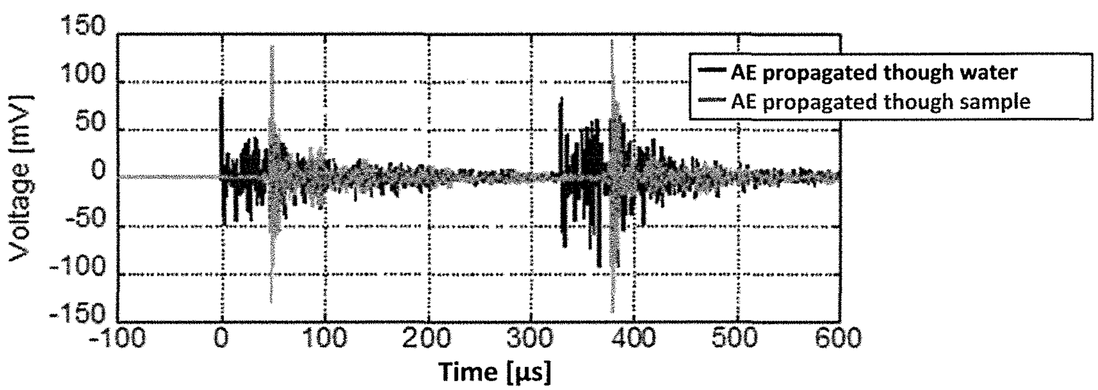

Fig. 2 Example of detected AE waveforms

• *Source location*

One benefit of using several AE sensors is an ability of source location. Based on the experimental setting as shown in Fig 1(a), four AE waveforms were detected from four AE sensors located at different positions inside the tank. The AE source location could be determined by the difference in hit arrival time among the sensors and the wave velocity in the water. Laser irradiations were performed at five different positions on sample surface and the source location was performed. The results showed a good agreement between the positions of laser irradiation observed from microscope and those obtained from AE source location with an error of ±2 mm. This implied that using multi-AE channel setting in the water tank provides good performance for in-process LSP monitoring.

• *Effect of sensor position*

Fig. 3 showed plots of maximum amplitudes of AE events generated from laser ablation as a function of source-to-sensor distance at various angles and power density. Maximum amplitudes tended to increase with power density and decease with increasing source-to-sensor distance for all angle positions. However, manners of amplitude decreasing were quite different depending on the position of the sensor. For example, at a source-to-sensor distance of ~30 mm, the discrepancies of the maximum amplitudes of AE waveforms detected by using laser energies of 0.35 and 4.7 GW/cm^2 were approximately 600, 300 and 200 mV for sensor setting located at near surface, 45°, and 75°, respectively. This discrepancy was probably related to the wave propagation behavior in the water.

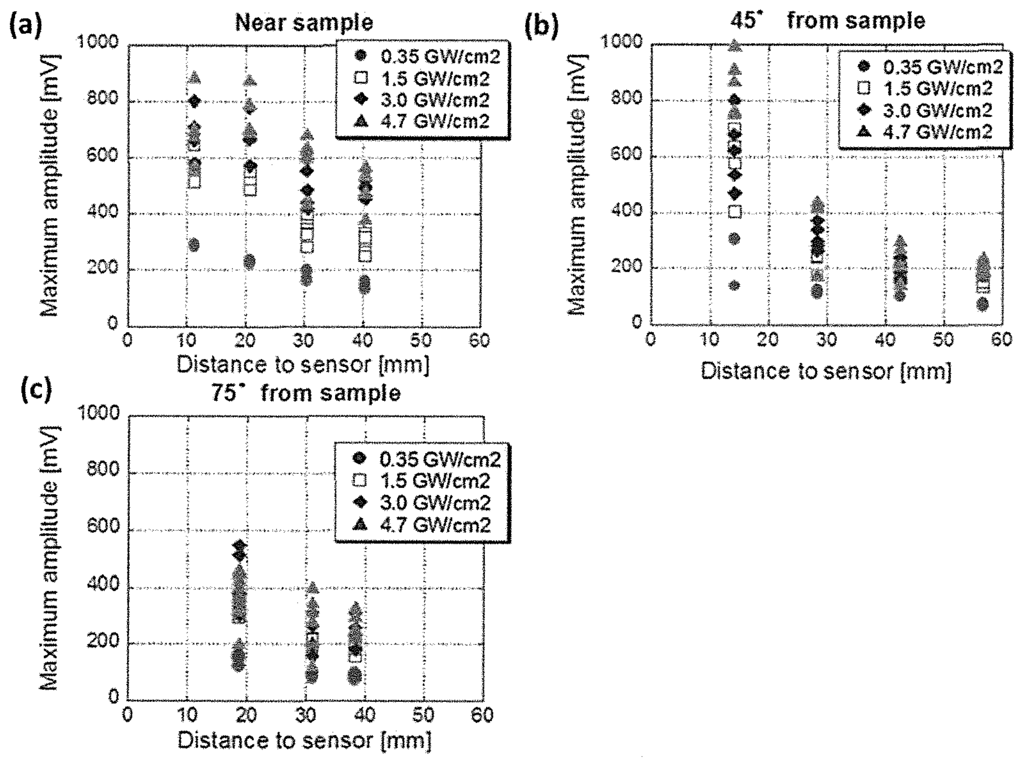

Fig. 3 Maximum amplitudes of detected AE events by laser ablation each sensor, (a) near the sample, (b) 45° from sample, (c) 75° from sample

• *Pressure estimation from inverse analysis*

Fig. 4 shows plots of pressure calculated by inverse analysis of AE events generated from laser ablation as a function of power density at various sensor positions. The results obtained from the sensor attached on the sample surface are also given in Fig. 4(d) for a comparison. The pressure tended to increase with power density of laser for all sensor positions. It seemed that the scattering of pressure became pronounced with increasing power density. This was due to an increase of absolute value. The improvement of experimental setting is required to minimize these errors. It should be noted that while the plot of maximum amplitude as shown in Fig 3 showed a strong effect of sensor position, there was small effect for pressure. Although there were scattering in the data, it said that the same pressure values could be obtained independently on the sensor position. Therefore, it can be implied that that inverse analysis was able to correct the differences between detected AE events at each sensor position in the water tank.

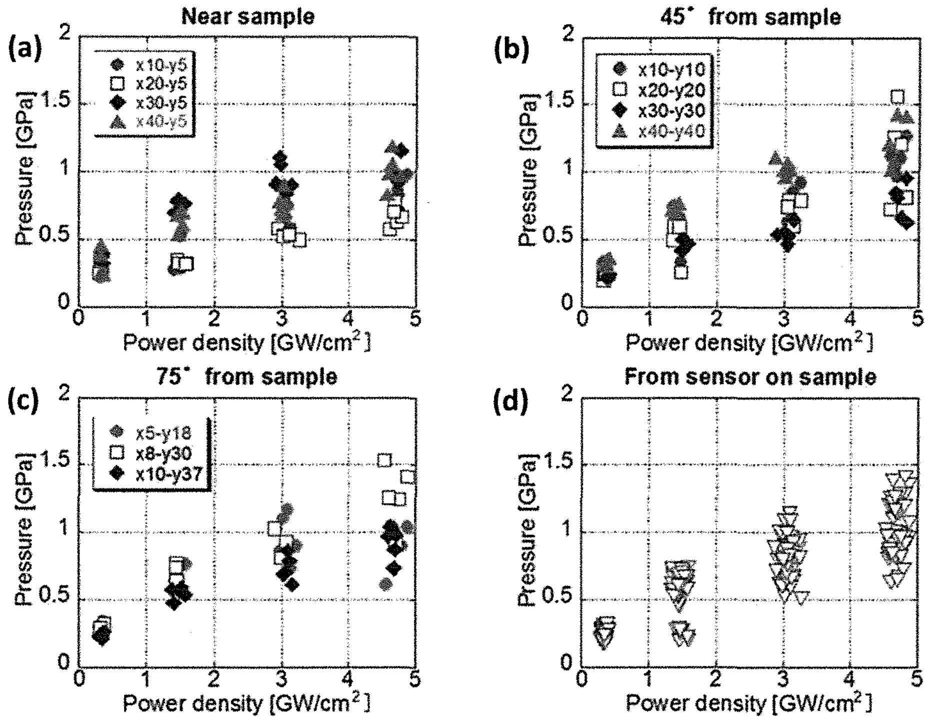

Fig. 4 Pressure by laser ablation each sensor, (a) near the sample, (b) 45° from sample, (c) 75° from sample, (d) on sample

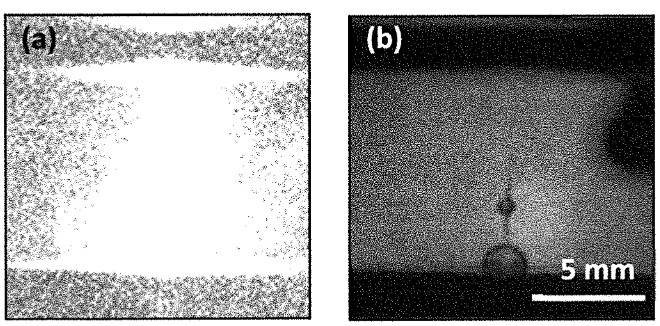

Fig. 5 High speed camera observation showing (a) laser-induced breakdown and (b) bubble formation after 26 µs from laser irradiation

• *Detection of laser-induced breakdown*

Fig. 5(a) shows the laser-induced breakdown observed by high speed camera. This breakdown was intentionally generated by focusing laser beam to the 4-mm upper position from the sample surface with maximum laser energy. The noise signal in this figure was due to laser light. After breakdown for 26 µs, bubble formation was observed as shown in Fig. 5(b). The previous section show that when the laser was focused on the sample surface, AEs generated from laser ablation could be detected from both sensors attached on the sample surface and those located in water tank. However, only sensor located in water tank could detect the AE from laser-induced breakdown. A possible explanation for this finding was that this breakdown occurred in water and then AE source was in the water too. Therefore it was difficult for this AE to be detected by the sensor attached on the sample surface because AE had to propagate from water into sample. Most of signal might reflect at the sample surface. It clearly showed that setting AE sensors in the water is able to detect process uncertainty such as laser-induced breakdown.

• *Performance of AE monitoring in water for LSP*
Several findings in the previous section have shown that setting AE sensors in the water instead of direct attaching on the sample surface provides various benefits such as capability of location, laser-induced breakdown detection. The pressure values estimated from the inverse analysis from the AE events detected from various sensor positions also showed a good agreement with those obtained from the sensor attached on the sample surface. This infers that AE monitoring in water is a powerful tool for LPS. The on-line process monitoring to control the quality of LSP is expected to be available by this technique.

Conclusions

The phenomena during LSP were evaluated by monitoring and analysis of AE propagated though water. The results obtained from this research are as follows:

1. Source location results from detected AE waveforms with four sensor set in tank were in good agreements with laser irradiation points.
2. Laser-induced breakdown is detected more obviously by measurement of AE propagated though water.
3. The calculated pressure by AE increased with power density of laser for all sensor positions. It is said that the differences between detected AE events at different positions of the sensors in water were corrected by inverse analysis.
4. These results show that monitoring of AE propagated though water is available to evaluate LSP.

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