Mechanical Surface Treatment of Duralumin Plate by Bubble Induced by Pulse Laser

H Soyama\(^1\), H Sasaki\(^2\), S Endo\(^3\) and Y Iga\(^4\)
\(^1\) Professor, Department of Nanomechanics, Tohoku University, Sendai, Japan
\(^2\) Ph. D. Student, Graduate School of Engineering, Tohoku University, Sendai, Japan
\(^3\) Graduate Student, Graduate School of Engineering, Tohoku University, Sendai, Japan
\(^4\) Associate Professor, Institute of Fluid Science, Tohoku University, Sendai, Japan

E-mail: soyama@mm.mech.tohoku.ac.jp

Abstract. Surface of duralumin plate can be treated by not only laser abrasion but also bubble induced by pulse laser. The pulse laser produced two kinds of shock waves related to laser abrasion and bubble collapse. In the case of laser peening, the shock wave induced by abrasion was normally used. In the present paper, the behaviour of bubble was observed and noise was detected by the hydrophone. It was revealed that the impact induced by the bubble collapse produced by the pulse laser was stronger than that of the laser abrasion. A numerical simulation was also carried out to investigate phenomenon of bubble collapse.

1. Introduction
Pulse laser is utilized for mechanical surface treatment, i.e., laser peening [1-3]. In the case of laser peening, shock wave induced by laser abrasion is used. As well known, bubble is also produced by pulse laser [4], and it develops and collapses as same as cavitation bubble. In the present paper, the bubble induced by pulse laser was called as laser cavitation. The shock wave induced by laser cavitation can be used for the mechanical surface treatment, as hydrodynamic cavitation was applied for mechanical surface treatment, i.e., cavitation peening [5, 6].

Laser peening methods can be classified two types. In order to confine shock wave induced by pulse laser, one type of them uses a water film on target with pulse laser, and the other type uses a water filled chamber. The bubble cannot be developed in a water film type, as the water film is broken by the laser abrasion. However, the laser cavitation can be developed in the water filled chamber type. Although it was reported that the shock wave induced laser abrasion was larger than that of the bubble collapse [7], it might be possible to enhance an impact at bubble collapse.

In the present paper, the laser cavitation was observed by a high speed video camera with noise which corresponded to the shock wave, comparing with shock wave generated by a laser abrasion. A numerical simulation was also carried out in order to investigate behaviour of bubble collapse.

2. Experimental apparatus and procedures
Figure 1 illustrates a schematic diagram of pulse laser system, in which Nd:YAG laser with Q-switch was used. The wave length, the maximum energy, the beam diameter, the pulse width and the repetition frequency were 532 nm, 0.2 J, 6 mm, 10 Hz and 5 ns, respectively. The pulse laser was irradiated to a target which was place in a water filled chamber made of quartz glass. The focal length of final convex lens was 100 mm. The distances from the final lens to the target \( S_{\text{Laser}} \) was 102 mm,
which was optimized by evaluating peening intensity changing with $S_{\text{Laser}}$. The above mentioned $S_{\text{Laser}} = 102$ mm was chosen by measuring maximum arc height of duralumin plate changing with $S_{\text{Laser}}$.

The laser cavitation was observed by a high speed video camera whose maximum framing rate was 230,000 frames per second with noise detected by a hydrophone.

In order to demonstrate mechanical surface treatment by the present pulse laser system, duralumin plate A2017-T3 whose thickness was 3 mm was treated, and the arc height was measured, then the inverse of curvature was calculated to show the peening effect.

A numerical simulation was also carried out for the collapse stage of the hemispherical vapour bubble on a wall. A simple numerical method for gas-liquid two-phase / material coupling analysis was applied [8], in the fluid analysis, locally homogeneous model was used and the bubble interface was expressed by gradient of void fraction. And compressibility was considered in liquid phase and gas phase was assumed as ideal-gas. In the material analysis, homogeneous isotropic elastic body was assumed and propagation of stress wave was reproduced numerically.

3. Results

In order to reveal effect of mechanical surface treatment by the pulse laser system, Fig. 2 shows the arc height of duralumin plate changing with density of pulse laser. The pulse laser produced a curvature of the duralumin plate. That means the present pulse laser system can introduce compressive residual stress. Namely, the present system can be applied for mechanical surface treatment of metals.

Figure 3 reveals the noise level $p_N$ detected by the hydrophone changing with time $t$ after irradiated pulse laser. The 1st and 2nd peaks were observed at $t \approx 0$ ms and 0.68 ms. Regarding Fig. 4, which shows the aspect of laser induced bubble, it was revealed that the 1st peak was related to laser abrasion and the 2nd peak was produced by the collapse of the laser cavitation. Note that the amplitude of the 2nd peak $p_N^{2\text{nd}}$ was larger than that of 1st peak $p_N^{1\text{st}}$. Namely, the shock wave induced by laser cavitation was stronger than that of laser abrasion.
In order to investigate key parameter of amplitude of 2nd peak of the noise, the bubble size and the noise level were measured changing with energy of pulse laser $E_{PL}$. Figure 5 reveals the noise level at 2nd peak $p_{N2nd}$ as a function of volume of bubble at the maximum size $V_{max}$. When $V_{max}$ was larger, $p_{N2nd}$ was larger. However, $p_{N2nd}$ seems to be saturated at large $V_{max}$ in the present condition. The correlation coefficient $r^2$ of the relation between $V_{max}$ and $p_{N2nd}$ was about 0.66 for 15 points.

Figure 6 shows the relation between the noise level at 1st peak $p_{N1st}$ and the noise level at 2nd peak $p_{N2nd}$. As shown in Fig. 6, $p_{N2nd}$ was increased with an increase of $p_{N1st}$. The $r^2$ of the relation between $p_{N1st}$ and $p_{N2nd}$ was 0.76, which was better than that of between $V_{max}$ and $p_{N2nd}$. It might be happepd that the inside pressure of the bubble at large $p_{N1st}$ would be less than that at low $p_{N1st}$, as noise at 1st peak was generated by the laser abrasion. Namely, the laser abrasion produced negative pressure wave just after shock wave, and the negative pressure would be larger when the shock wave, i.e., $p_{N1st}$ was larger. Thus, pressure difference between inside and outside of bubble would be large at large $p_{N1st}$ at the time of maximum bubble radius because of drastic growth of the bubble. It can be concluded that the large pressure difference might produce large impact at bubble collapse. These experimental result was examined by following numerical simulation.

A numerical simulation was also carried out for the collapse stage of the hemispherical vapour bubble on a wall. A simple numerical method for gas-liquid two-phase / material coupling analysis was applied [8], in the fluid analysis, locally homogeneous model was used and the bubble interface was expressed by gradient of void fraction. And compressibility was considered in liquid phase and

**Figure 4.** Aspect of laser cavitation (laser induced bubble).

**Figure 5.** Noise level at 2nd peak as a function of maximum volume of bubble

**Figure 6.** Noise level at 2nd peak as a function of noise level at 1st peak

**Figure 7.** Aspect of bubble collapse (Upper: fluid, lower: material, Initial condition: radius 3.6 mm, bubble pressure 2,300 Pa, ambient pressure 0.1 MPa, temperature 293.15 K)
gas phase was assumed as ideal-gas. In the material analysis, homogeneous isotropic elastic body was assumed and propagation of stress wave was reproduced numerically. In Fig. 7, time evolution of aspect of bubble collapse is shown in a case of initial bubble radius 3.6 mm. Pressure contour distribution and iso-void fraction line at 0.5 are shown in fluid (upper) and equivalent stress is shown in material (lower). In Fig. 7, (a) is the time of maximum radius, (b) is half radius, at the time (c) maximum collapse pressure occurs in fluid and maximum equivalent stress is yielded in material, after that, bubble starts rebound, pressure wave propagates in liquid and stress wave propagates in material at the time (d).

Next, time evolution of bubble radius, centre pressure and centre temperature inside a bubble at the collapse stage are shown in Fig. 8 with varying initial pressure difference. As show in the figure, higher pressure and higher temperature is caused by higher pressure difference condition although initial bubble radiiuses are same. Besides, because ideal gas was assumed for vapour inside the bubble, the maximum values were not accurate at such a high pressure and high temperature condition at final stage of bubble collapse. But relative evaluation was considered to be effective. In a future work, influences will be analysed for ambient void fraction which corresponds residual bubble nuclei, temperature and flow field around a bubble. In addition, the tendency that higher pressure difference produced higher pressure at bubble collapse well corresponded to above mentioned experimental results.

4. Conclusions
In order to demonstrate the possibility of bubble induced by pulse laser, i.e., laser cavitation, for mechanical surface treatment, the high speed observation was carried out with detecting the noise, which corresponded to the shock wave, evaluating peening intensity by curvature of duralumin plate. The numerical simulation was also carried out for a behaviour of bubble collapse, pressure and temperature distribution inside the hemispherical vapour bubble, and equivalent stress distribution in the material were analysed. It was concluded that the pulse laser at the present condition can be applied for the peening and impact induced by the laser cavitation was larger than that of laser abrasion.

This work was partially supported by The Amada Foundation and The New Technology Development Foundation. The authors thank Mr. M. Mikami, technician, and Mr. Y. Ueno, graduate student, Tohoku University for their help with the experiment.

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