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Experimental investigation on dynamic characteristics and strengthening mechanism of laser-induced cavitation bubbles

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ABSTRACT

The dynamic features of nanosecond laser-induced cavitation bubbles near the light alloy boundary were investigated with the high-speed photography. The shock-waves and the dynamic characteristics of the cavitation bubbles generated by the laser were detected using the hydrophone. The dynamic features and strengthening mechanism of cavitation bubbles were studied. The strengthening mechanisms of cavitation bubble were discussed when the relative distance parameter γ was within the range of 0.5–2.5. It showed that the strengthening mechanisms caused by liquid jet or shock-waves depended on γ much. The research results provided a new strengthening method based on laser-induced cavitation shotless peening (CSP).

1. Introduction

Theoretical interest in single cavitation bubble traces back to the last century [1]. The researches in this field usually focused on the damage or erosion caused by cavitation bubbles [2–5]. Some new research directions were proposed such as ultrasonic cleaning [6,7] and shock-wave lithotripsy [8] in recent years. The high-speed photography technology was generally used to detect the short duration of cavitation bubble process. Yang [2], Xu [9], and Zhao [10] employed high-speed photography and acoustic measurements technology to study the dynamic characteristics of cavitation bubbles near boundaries. Later on, Xu et al. improved the high-speed photography technology to observe the change process of the jet and reversed jet [11].

There are few researches using the cavitation bubble to strengthen the surface properties of the substrate. Liu et al. used a liquid jet produced by the collapse of a laser-induced bubble to investigate the effect on surface tension of copper target [12]. Soyama et al. found that cavitation shotless peening (CSP) is an effective method to improve the fatigue life of Duralumin plates [13,14].

In the present study, the cavitation bubble is generated by employing nanosecond laser pulses. The shock-waves and bubble evolution process are recorded by a high-speed camera with the frame rate of 200,000 fps. The residual stress is measured by the X-ray diffractometer. This study is aimed to investigate the strengthening mechanisms of cavitation bubbles and use laser-induced CSP method to strengthen the surface of the materials.

2. Experimental setups

2.1. Experimental material

The 1060 aluminum alloy with size of $50 \times 50 \times 0.5$ mm was used as the test specimen for its insensitive load rate of deformation force. Its chemical composition is shown in Table 1, and the mechanical properties at room temperature are shown in Table 2.

2.2. Experimental setups

The experiment system is schematically shown in Fig. 1. A Q-switched Nd: YAG laser with wavelength of 1064 nm and pulse duration of 10 ns is used to generate cavitation bubbles. The expanding lens system is employed to adjust the energy density without changing spatial distribution.

The aluminum target is put into the glass cuvette ($200 \times 200 \times 120\ mm^3$) filled with water. The laser beam goes through a negative lens and then is focused on the aluminum surface in water. High temperature plasma would be induced if the laser power density at focus point exceeds the breakdown threshold of the liquid. The plasma expands towards outside at supersonic speed to form a cavitation bubble with high temperature and pressure.

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Table 1
Chemical compositions of 1060 aluminum alloy (wt.%).

Cu	Mn	Mg	Zn	V	Ti	Si	Fe	Al
⩽0.05	⩽0.05	⩽0.05	⩽0.05	⩽0.05	⩽0.03	⩽0.25	0–0.4	Balance

Table 2
Mechanical properties of 1060 aluminum alloy.

Material	Tensile strength σ_b (MPa)	Yield strength $\sigma_{0.2}$ (MPa)	Elongation δ_5 (%)
1060 aluminum	95–125	⩾75	30–50

Fig. 2(a) shows that the breakdown region is in the shape of strip around the focus point, which is adverse to the research of single cavitation bubble. The expanding lens system is employed to adjust the laser beam to obtain a single breakdown cavitation bubble shown in Fig. 2(b).

A high-speed camera (V2511, Phantom, USA) with an image resolution of 128 × 128 pixels is adopted to obtain the clear dynamic features of cavitation bubbles induced by pulsed laser. Laser light source (Cavitar, Finland) is chosen in the experiment for its superior synchronism with the high-speed camera. In addition, the plasma shock-wave generated by laser and the stress wave signal radiated in the compression process of cavitation bubbles are measured by a hydrophone (NCS-1, China) with frequency range of 0.5–15 MHz. The oscilloscope (DL9140) with bandwidth up to 1 GHz is used to connect the hydrophone. The compressive residual stress in the target is measured by the X-350A ray stress analyzer with diffraction crystal plane of (311) and the scanning angle is from 136° to 142°.

3. Results and analysis

3.1. Shock-waves

Fig. 3 shows shock-waves signal detected by NCS-1 hydrophone for the laser energy of 200 mJ and $H = 1.5$ mm (H is the standoff distance between cavitation bubble center and the target surface). There are two shock-wave peaks and the time interval is 182 μs. With other experimental conditions unchanged, the water in the glass cuvette is drained out so that the laser can shock the target surface directly. This can rule out the possibility that the second peak of shock-wave is the reflected wave caused by target surface or cuvette wall. By doing this, only one peak of shock-wave is displayed on the oscilloscope [15]. It could be determined that the first peak of shock-wave is generated by laser, and the second peak is produced during the rebound and collapse process of the cavitation bubble. The shock-waves indicated by white arrows in Fig. 3 are recorded by the high-speed camera. As the cavitation bubble develops near the target surface, the shock-wave intensity of pressure is relatively small. While the microjet induced by cavitation bubble has formed and would shock the target surface fleetly. Therefore, the main reason to strengthen the target surface is the microjet of cavitation bubble. But the impact of rebound on target surface induced by cavitation bubble could not be ignored when it has a certain standoff distance between cavitation bubble center and the target surface.

The maximum radius of the cavitation bubble can be calculated according to the shock-wave signal measured by oscilloscope and Rayleigh formula derivation. The Rayleigh formula derivation based on the cavitation bubble theory is listed as follows [16],

$$R_{max} = \frac{T_c}{0.915\sqrt{\rho/(P_\infty - P_0)}} \tag{1}$$

$$E_{Bi} = \frac{4}{3}(P_\infty - P_0)R_{max}^3 \tag{2}$$

where, R_{max} is the maximum radius of the cavitation bubble. T_c is the cavitation bubble oscillation period. ρ is the density of water. P_0 is vapor pressure in cavitation bubbles (P_0 equals to 2330 Pa when the temperature is 20 °C). P_∞ is static pressure in water (P_∞ is 100,000 Pa), and E_{Bi} is the energy of cavitation bubble. Here, $T_c = \frac{1}{2}T = 91$ μs, and the relative distance parameter $\gamma = \frac{H}{R_{max}} = 1.5$.

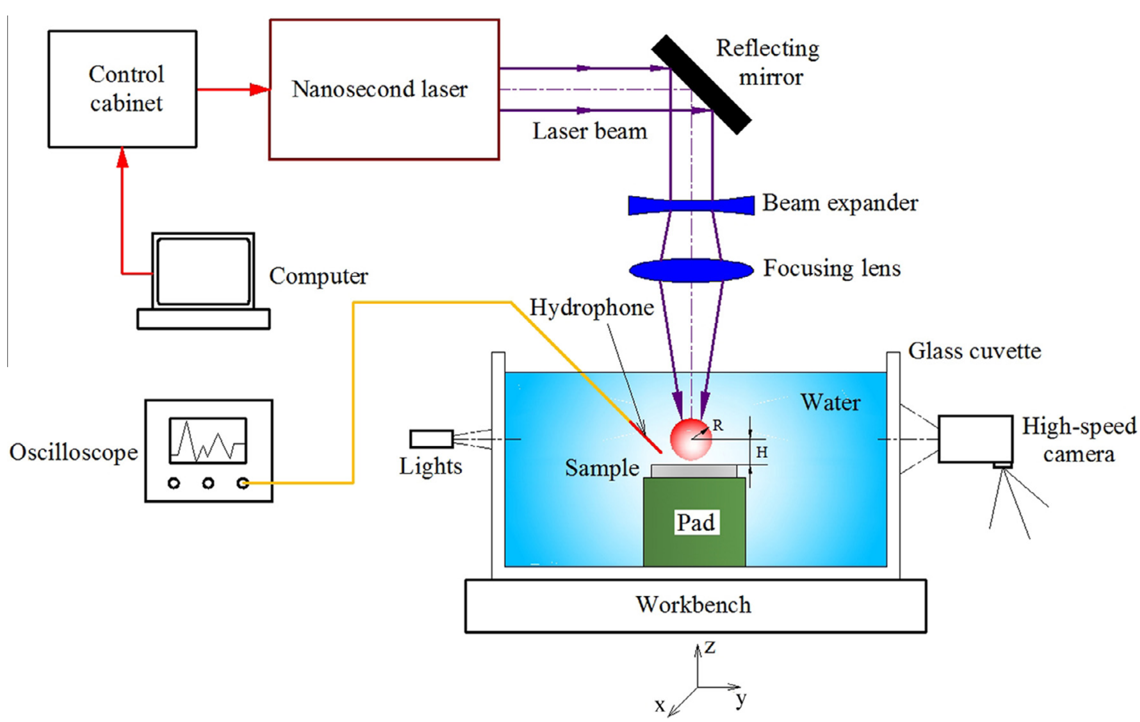

Fig. 1. Diagram of the laser-induced cavitation bubble peening.