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Mechanical effect of laser-induced cavitation bubble of 2A02 alloy

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ABSTRACT

Cavitation Shotless Peening is a process that can be used to strengthen a material. The mechanical effects are investigated in this paper. Sclerometer and X-ray diffraction (XRD) were used to study the mechanical property of the samples treated by laser-induced cavitation bubble. The results indicate that the change of micro-hardness in the depth and the horizontal directions of samples treated by Cavitation Shotless Peening are more obvious with the increase of laser energy. The depth of the strengthened layer increases with an increase in laser energy. And the best position of intensified effect is that the defocusing amount is equal to 1 mm. The researches provide a new high efficient method to strengthen the material.

1. Introduction

Cavitation exist in our daily life, and it was discovered earlier by Euler in 1753 [1]. The phenomenon can lead to serious damage in many hydraulic machinery, especially the pump, propeller and submarine. Euler found that when the pressure in the water pipe is as low as 0 Pa, which is a vacuum state, the water will be separated from the pipe wall [2]. In 1897, Parsons and Barnaby defined this phenomenon as "cavitation" for the first time and pointed out the necessary conditions for the formation of cavitation [3]. On the basis of Rayleigh equation, Plesset took into account the dynamic characteristics of the pressure in the bubble and then derived the well-known Rayleigh-Plesset equation in 1949 [4–6].

In 1873, Reynolds began to study the cavitation in the laboratory. Philipp et al. studied the laser-induced cavitation erosion [7]. Kling used high-speed photography method which can capture the collapse process of the bubble induced by an electric spark in 1972 [8]. Vogel et al. got the details of the collapse process near the solid wall and the rebound phenomenon from millions of frame images of the film [9]. Tomita and Shima pointed out that the jet will impact on the solid wall when the distance between the center of the bubble and the solid wall is in a certain range [10].

Since the latter half of the nineteenth century, cavitation has been a particular concern in the field of fluid. The assumption has been widely recognized by the academic community that the bubble collapse accompanied by the shockwave and high-speed jet are the cause of cavitation erosion. However, most of the researches are focusing on the cavitation erosion and the method to avoid it. There is little work published on how to make the best use of the cavitation. It is well known that the traditional methods to strengthen the metal materials are shot peening and laser shock processing [11–13]. Both methods use the impact force to strengthen the metal material, that eventually improve the residual stress distribution and increase the yield strength. The bubble collapse will contribute to the shockwave and micro-jet that can also strengthen the material with the similar mechanism [14,15]. Scholars have made a lot of researches on this kind of mechanism [16]. In 2000, Soyama et al. made the nozzle into an elongated cylinder to produce the high-speed water jet impacting on the surface of high-speed steel. After being treated, plastic deformation and the residual stress could be detected on the surface of the sample [17]. This shows that cavitation can indeed play a significant role in strengthening the surface of the material under certain conditions and this process is termed as "Cavitation Shotless Peening (CSP)". Because of the Spherical symmetries and the controllability of the cavitation bubble induced by the laser, most scholars do the research by using experimental method [18–21].

In this paper, the mechanical effects and strengthening mechanism of 2A02 alloy treated by the cavitation bubble with different laser energy and defocusing amount ("H") were investigated. Also, this paper investigates effects of cavitation bubble on micro-hardness and residual stress of the alloy treated in different conditions. All these will help to analyze the strengthening mechanism of CSP and the corrosion resistance of materials.

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2. Experiments

2.1. Material and testing parameters

The material used in this experiment is 2A02 aluminum alloy. Table 1 and Table 2 show the chemical compositions and the mechanical properties of the sample respectively.

To explore the impact of cavitation bubble on the samples, the 2A02 aluminum alloy samples were cut into 10 mm × 10 mm × 5mm. The sample surface was polished by sandpapers to make it smooth, then annealed in the resistance furnace to release the residual stress. Finally, the samples were cleaned in anhydrous alcohol.

The machining patch is showed in Fig. 1.The five circles marked from 1 to 5 respectively represent different treated zones, and the corresponding laser energy is from 100 mJ to 500 mJ, which increases by the step of 100 mJ. To acquire the influence of defocusing amount on the CSP, five samples treated in different defocusing amounts are prepared and labeled as A, B, C, D and E. The defocusing amounts are 0 mm, 0.5 mm, 1 mm, 1.5 mm and 2 mm, respectively.

2.2. Experimental equipment and methods

The experimental setup includes a nanosecond laser, a high-speed camera and an oscilloscope. The laser energy can be up to 1.2 J and that is available to breakdown the water. The high-speed camera and the oscilloscope were used to investigate the pulsation of cavitation bubble that was used to strengthen the samples. After CSP treatment, the samples were cut off along the center of the treated zone of the surface to measure the hardness and residual stress in the depth direction. The experimental setup is shown in Fig. 2. The mechanical properties of the samples were examined after the CSP treatment process. OLYMPUS-DSX500 optical microscope was used to test the surface morphology of the material. Roughness tester type NDT110 was used to test the surface roughness of the material. Surface micro-hardness of the samples was tested with HXD-1000TMSC/LCD micro-hardness tester.

3. Results and discussions

3.1. Shockwave signal

In this paper, the hydrophone was used to detect the acoustic signal. As shown in Fig. 3, there are two peaks labeled as peak 1 and 2 respectively. The plasma will only occur when the laser energy is higher than the breakdown threshold of water [18]. Absorbing the laser energy, the plasma will continue to expand, and that will lead to the formation of the cavitation bubble and shockwave . The hydrophone then captures the shockwave. When the cavitation bubble enlarges, the pressure inside becomes smaller than the pressure of the water. This leads to the shrinkage of the cavitation bubble that eventually radiate the shockwave. Then the hydrophone captures the shockwave after 498 μs later. If the sensitivity of the hydrophone is high enough, a number of small peaks caused by the background noise can also be detected for the subsequent pulsation process.

Table 2
Mechanical properties of 2A02 aluminum alloy.

Material	Tensile strength σ_b (MPa)	Yield strength $\sigma_{0.2}$ (MPa)	Elongation σ_5 (%)
2A02 Al alloy	≥430	280	≥10

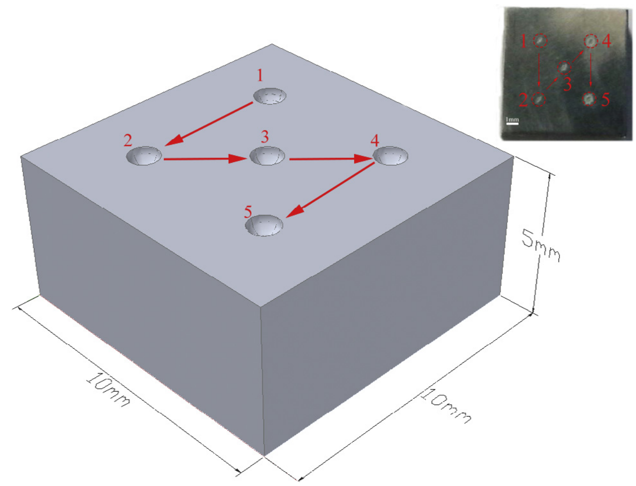

Fig. 1. Surface topography of the sample. The arrow show the route map of CSP. The sample strengthened with H = 0 mm. (the laser energy used to strengthen the first area was 100 mJ; the second one was 200 mJ; the third was 300 mJ; the forth one was 400 mJ; the fifth one was 500 mJ).

3.2. Surface morphology and roughness

The surface morphology of the treated samples were observed to have been changed. Fig. 4 shows the section profile of the samples treated with different laser energy. It can be seen that the wavy morphology of the treated area is enlarged both in the depth and the horizontal directions. The fluctuation degree of the curve is relatively flat with low laser energy and increases with an increase in laser energy. Tiny pits were formed after the samples were treated, and the inhomogeneous plastic deformation that occurred on the surface layer changed the surface morphology of the samples.

The roughness of the samples were measured from the center of the treated surface at every 5 μm from both sides and this is shown in Fig. 5. It can be seen from the figure that the surface of the sample is relatively rough after it was treated with CSP. The roughness of the treated area increased with an increase in laser energy, but the roughness level at the center of the treated spot is the smallest. This change can be attribute to the shockwave and micro-jet that increased the roughness for the emerging of slag around the treated area. Some experimental and simulated work have been published about the shockwave and the micro-jet that, the intensity of the shockwave can be up to 2200 atm and the velocity of the micro-jet can be faster than 1.5 km/s [22,23]. However, the intensity and the velocity can be reduced by adjusting the distance between the center of the bubble and the material surface. We can draw a conclusion from the section profile in Fig. 5 that the micro-jet played the main role in strengthening the sample in this experiment. Hence, the cavitation bubble can be used to strengthen the samples in a special condition.

Table 1
Chemical compositions of 2A02 aluminum alloy (wt.%).

Cu	Mg	Mn	Si	Fe	Ti	Be	Cr	Zn	Al
2.6–3.2	2.0–2.4	0.45–0.7	≤0.3	≤0.3	≤0.15	0.05	0.05	≤0.1	Other