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Impact of time on ultrasonic cavitation peening via detection of surface plastic deformation

Fushi Bai [a,*], Kai-Alexander Saalbach [a], Liang Wang [a,b], Xiaogeng Wang [a], Jens Twiefel [a]

[a] Institute of Dynamics and Vibration Research, Leibniz Universität Hannover, Appelstr. 11, Hannover 30167, Germany
[b] State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Yudao 29, Nanjing 210016, People's Republic of China

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ABSTRACT

During ultrasonic cavitation peening, bubbles repeatedly form and collapse, which leads to high impact loads on the treated surface. At the initial stage of ultrasonic cavitation peening, the most obvious change is plastic deformation instead of mass loss on the treated specimen surface. Meanwhile the plastic deformation is beneficial for mechanical surface properties. As the cavitation exposure time increases, erosion and damage are inflicted on the metal surface due to the increase in the number of collapse events. In this respect, the treatment time is a key parameter to improve the specimen surface properties during this manufacturing process. However, the influence of treatment time on the surface properties has not yet been thoroughly investigated. In this paper, it is the first time to utilize the plastic deformation to evaluate the optimal treatment time at different input power. The plastic deformation can be deduced by the mass loss and the volume change on the treated specimen surface. Using plastic deformation, the modification of surface hardness and roughness are investigated at different cavitation exposure intervals and vibration amplitudes. It is found that significant improvement of the microhardness on the treated surface occurs at the end of incubation period. Higher vibration amplitudes of the horn tip lead to shorter incubation period and higher microhardness.

1. Introduction

Ultrasonic cavitation peening can improve the metal surface properties in the same way as other traditional peening methods [1]. This novel technology was invented in the 1990s and the concept of ultrasonic cavitation peening was first proposed in 2007 [2], in which a piezoelectric transducer is utilized. Using a piezoelectric transducer has many advantages: it is easy to control, has a compact structure [3] as well as a high output power [4], etc. Due to the vibration of the transducer sonotrode, cavitation bubbles are generated in a thin gap. The gap is between the end of the sonotrode and the treated specimen surface and is usually less than 1 mm. After the collapse of cavitation bubbles, shock waves and micro jets [5] are generated, which introduces plastic deformations on the impacting surface. The deformations increase the residual stress, hardness and roughness [6]. As a result, the surface properties are improved. Since there are no solid objects bombarding the workpiece [7], the increase of surface roughness is smaller compared to other conventional peening processes [8]. At the end of ultrasonic cavitation peening, water only contains metal and metal oxide powder, which can be easily collected and recycled. Apart from this, this surface treatment process is low-cost to perform and occurs in only one step [9].

Ultrasonic cavitation peening takes the advantage of the initial stage of cavitation erosion on the metal surface. In reality, the cavitation erosion process follows four successive stages [10]: incubation period, acceleration period, deceleration period and steady-state period. The initial stage is called incubation period when much plastic deformation is generated while mass loss is negligible. As the exposure time continues, the erosion rate reaches the maximum whereas the rate of the plastic deformation decreases. This is the second stage of cavitation erosion called the acceleration period. In deceleration and steady-state periods, the erosion rate decreases and then stays steady. Therefore, the exposure time is significant for the improvement of the metal surface.

The effects of ultrasonic cavitation on the surface quality of AISI 4140 and AISI 1045 steels were first investigated by Mathias et al. [11]. It was found that similar deformation mechanisms existed in cavitation erosion and shot peening. The residual stress of AISI 304 stainless steel specimens treated by cavitation was detected as well [12]. Sasaki et al. [13] discussed the influence of cavitation

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[*] Corresponding author.
E-mail addresses: bai@ids.uni-hannover.de, baifushi@hotmail.com (F. Bai).

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peening on the fatigue property of cold-rolled stainless-steel sheet. It was found that the beam fatigue strength of a cavitation specimen was stronger than non-peened and shot-peened specimens. The compressive residual stresses were produced as a consequence of the volume change associated with the tetragonal–monoclinic phase transformation [14]. Meanwhile, the ultrasonic cavitation peening process obviously enhances the specimen surface hardness [15]. Kim et al. [16] found that weight loss increased with the increase of the temperatures, ultrasonic amplitudes, and experimental time. Sasaki et al. [17] used a concaved horn to increase the impact on the treated surface and Bai et al. [18] found that a standoff distance of less than 1 mm is beneficial for ultrasonic cavitation peening. Ultrasonic cavitation can also be use to improve the properties of deep notches [19]. The residual stress near the notch tip caused by cavitation bubbles during process was measured as well.

During ultrasonic cavitation peening, the end of the incubation period should be the optimal treated time, since at that moment much plastic deformation takes place while little mass loss is generated. However, it is difficult to decide when the incubation period ends by the measurement of volume change or mass loss, because both of them are successive. Here volume change means the volume difference before and after treatment. In this paper, the plastic deformation method is used to evaluate the incubation period for the first time. The plastic deformation is deduced by both volume change and mass loss. On the other hand, microhardness can be used to evaluate the effect of the ultrasonic cavitation peening process. In order to realize the material surface characterize in different intervals. The microhardness on treated surface was measured correspondingly. The surface roughness was measured as well. In the following sections, the novel method using plastic deformation is utilized to estimate the incubation time during ultrasonic cavitation. In order to obtain the optimal cavitation exposure time, the roughness and microhardness are investigated under different experimental conditions.

2. Experimental

The scheme of the ultrasonic cavitation apparatus used for cavitation peening is illustrated in Fig. 1. It is a classic sandwich transducer which was designed and manufactured at IDS and is driven at its longitudinal eigen mode at a vibration frequency of about 23 kHz. The transducer whose length equals one wavelength consists of an aluminum alloy tail-mass, four piezoelectric ceramics and a titanium alloy head-mass. The cavitation bubbles were generated by vibration via the ultrasonic horn with the tip diameter of 5 mm. The transducer was driven in resonance by a digital phase and amplitude control unit (IDS Digital-Phase Control 500/100k) [20] with a power amplifier QSC 4050.

Both phase feedback and current feedback control are applied for the investigations. With this setup, the ultrasonic transducer was always driven at resonance [22,23] even the load changes. A relationship of approximately 120 μm/A between vibration amplitude and driving current was determined. The driving currents in this work were 0.208 A, 0.250 A, 0292 A and 0.333 A, respectively. The corresponding input power to the driving currents was 12.7 W, 15.9 W, 19.3 W and 23 W, respectively. Fig. 2 shows the different working parameters at the driving current of 0.333 A. The phase and driving were controlled with the value of 0° and 0.333 A. At the beginning of ultrasonic cavitation, all the parameter had a transient change and then almost kept stable. The resonance frequency decreased slightly due to the temperature effect on the transducer.

The square specimen plates (10 mm × 10 mm), which are made of aluminum alloy 5005 with a polish surface (original roughness: 100 nm), were treated by ultrasonic cavitation peening. The physical properties are presented in Table 1.

The specimen was placed in a water container (Ø110mm × 90 mm) and 10 mm under the free liquid level. The width of the gap between the specimen surface and the ultrasonic sonotrode tip was 0.7 mm. The initial water temperature was 22 °C. Moreover, in order to minimize the influence of temperature, the water in the container was replaced after each measurement.

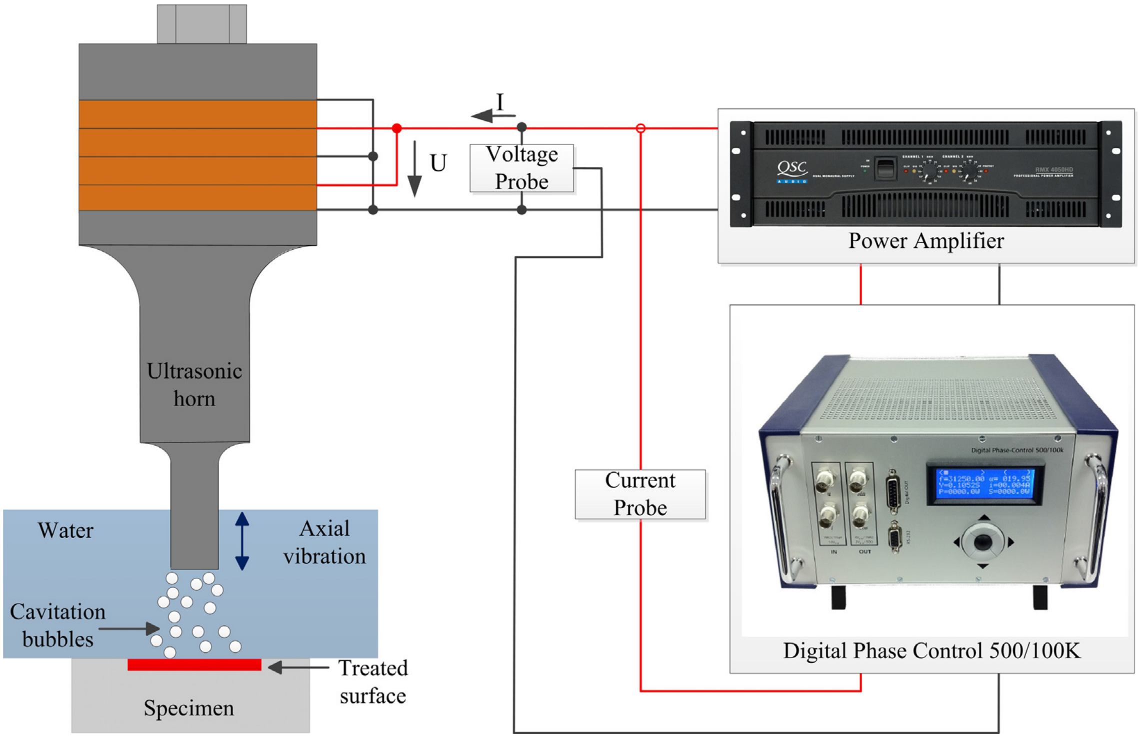

Fig. 1. The scheme of ultrasonic cavitation peening setup [21].