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Capability evaluation of ultrasonic cavitation peening at different standoff distances

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ABSTRACT

Ultrasonic cavitation peening is a novel surface treatment technology which utilizes the effect of cavitation bubble collapses to improve the properties of metal surfaces. In order to obtain high impact during ultrasonic cavitation peening, a small standoff distance between a sound radiator and a rigid reflector (the surface of treated specimen) is necessary. However, the effects of different standoff distances on the capability of ultrasonic cavitation peening are not yet clear. In this paper, a simplified model was developed to evaluate the cavitation capability at different standoff distances. Meanwhile, to validate the theoretical model, the plastic deformation or erosion on the peening surface before and after treatment were compared. It was found that at a very small standoff distance the impact pressure generated by cavitation bubbles did not cause much deformation or erosion, as the dynamics of cavitation bubbles was limited. At a large standoff distance, due to much attenuation of sound propagation in the bubbly liquid, little impact pressure was generated by the collapse of cavitation bubbles and reached the treated surface. A fixed vibration amplitude, however, corresponded to a standoff distance which caused the largest deformation or erosion on the treated surface.

1. Introduction

Ultrasonic cavitation peening is a potential technology that can be used for mechanical surface treatment. During the ultrasonic cavitation peening process, cavitation bubbles grow and then collapse violently [1,2,3]. This generates a high amount of pressure on the peeing surface, the reliability of which will thus be significantly enhanced.

It is well known that cavitation bubbles cause erosion on metal surfaces. In reality, there are four successive stages during cavitation erosion [4]: (1) incubation period, (2) acceleration period, (3) deceleration period and (4) steady-state period. In the first stage, much plastic deformation is caused while mass loss is negligible. As the peening process continues to the following three stages, the mass loss becomes more significant, which is not desired. Therefore, ultrasonic cavitation peening has the advantage of an incubation period by which the compressive residual stress and the hardness are increased while the mass loss is negligible. It is similar to the traditional shot peening methods, however ultrasonic cavitation peening only utilizes liquid that generates little pollution during the peening process. In addition, the roughness of the treated surface is less significant than that caused by other peening technologies [5], which is another advantage of ultrasonic cavitation peening.

Already much work has been carried out to improve this novel technology. Mathias et al. [6] was the first to explore the effects of ultrasonic cavitation on the surface quality of AISI 4140 and AISI 1045 steels at a standoff distance of 0.7 mm. It has been pointed out that shock waves during the incubation period are the main cause leading to the plastic deformation of the material. Here the standoff distance, a key parameter of ultrasonic cavitation peening, is defined as the width of the gap between the horn tip and the treated surface. A standoff distance of 1.5 mm was used to treat the surface of AISI 304 stainless steel specimens and the residual stress due to ultrasonic cavitation was also detected by ultrasonic cavitation [7]. The concept of ultrasonic cavitation peening was first proposed by Toh [8]. Gao et al. [9] measured the surface hardness, profile, and roughness of different workpiece surfaces before and after ultrasonic cavitation peening, during which the specimen was positioned in a holder facing the horn tip at a standoff distance of 1 mm. It was found that the properties of the surfaces were greatly improved. Sasaki et al. [10] discussed the influence of cavitation peening on the fatigue property of cold-rolled stainless-steel sheet at a standoff distance of 1 mm. Then they used a piezoelectric force sensor to study the effect within the standoff distance range of 0.5–4 mm [11]. From this contribution, the highest impact

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was obtained at the standoff distance of 1 mm. Kim et al. [12] used a standoff distance of approximately 1 mm to investigate the damage behavior of Al alloy by ultrasonic cavitation. They found that the loss of weight increased with the increase in ultrasonic amplitudes and experiment time. Bai et al. found that it is easier to control the transducer at the standoff distance of 1 mm [13] during ultrasonic cavitation peening.

During ultrasonic cavitation peening, attenuation of sound propagation and energy loss are caused by cavitation bubbles. As a result, the thickness of the cavitation liquid layer plays an important role on the surface treatment quality. It must be pointed out that the cavitation liquid layers in various thicknesses not only have some new process characteristics but also produce different treatment results. The literature [6–13] mentioned above has taken different experimental parameters (i.e. frequency, temperature and vibration amplitude) into consideration, but the emphasis has not yet been placed on the standoff distance. Meanwhile, the standoff distance is a special parameter for investigating ultrasonic cavitation peening compared to other cavitation applications since small standoff distance is necessary during ultrasonic cavitation peening. A fixed standoff distance was normally used in the above researches, but the reason for selecting the fixed standoff distance was not described. Hence, the responses of treated surfaces to different standoff distances are worth deeper investigation. Furthermore, it is important to determine the corresponding standoff distance that works best with a fixed vibration amplitude during ultrasonic cavitation peening. In this paper, a simplified model is established in order to describe the effect of different standoff distances during ultrasonic cavitation peening and the relationship between the vibration amplitude of transducer and the optimal standoff distance. The volume changes of peening specimens are used to validate the theoretical model results.

2. Theoretical analysis

During the ultrasonic cavitation peening process, a small standoff distance between the workpiece surface and the ultrasonic horn tip is generally used to avoid undesired energy loss. However, even a small change in the standoff distance significantly affects the dynamics of cavitation bubbles. Consequently, the capability of ultrasonic cavitation peening greatly changes with various standoff distances due to the attenuation of wave propagation and the limitation of bubble dynamics. The aim of this section is to provide a theoretical model to analyze the cavitation capability at different standoff distances.

There is a large number of cavitation bubbles in cavitation fields, which changes the velocity of sound propagation. Based on the equations of mass and momentum conservation and the barotropic law, the sound velocity in ultrasonic cavitation field [14] can be described as:

$$\frac{1}{c^2} = \{\beta\rho_v + (1-\beta)\rho_l\}\left[\frac{\beta}{\rho_v c_v^2} + \frac{1-\beta}{\rho_l c_l^2}\right] \tag{1}$$

where ρ_v is the density of the vapor and ρ_l is the density of the liquid. C_v and c_l are the sound speed in the vapor and in the pure liquid, respectively. β is the fraction of volume occupied by gas. A linear relationship of approximately 2×10^{-9}/Pa between the bubble volume fraction β and the acoustic pressure amplitude p is determined [15]. Because of changes in the bubble volume fraction, a new pressure field has to be obtained to reach a steady state. In this work, it is assumed that the volume fraction is unchanged from the initial state. The speed of sound in cavitation liquid can then be calculated.

At the same time, when a sound wave travels through the liquid filled with cavitation, an increase in the local temperature is caused. The scattering, absorption and reflection of the incident wave also contribute to the loss of intensity. A function of the attenuation coefficient was provided [16],

$$\alpha_f = \frac{\omega^2 \mu b^*}{2\rho c^3} \tag{2}$$

where α_f is the attenuation coefficient; ω is the angular frequency of irradiation, μ is the bulk viscosity of liquid; b^* is a constant ($b^* = 4/3 \times 10^7$ for water containing cavitation bubbles), ρ and c are the density of liquid and the sound speed in liquid, respectively.

Since the vibration of the horn tip is piston-like, the wave is considered a plane wave. Therefore, cylindrical coordinates (r, θ, z) are used, where r is the radius from the center of horn tip, θ the angle of that radius, and z a length in the direction perpendicular to the specimen surface. It is assumed that the radiation surface is a fixed rigid wall at $z = 0$ and that the specimen surface is a rigid wall as well. The sound wave travels though the cavitation field in z direction from the radiation surface. Then it is reflected by the specimen surface at $z = L$ and propagates towards the radiation surface again. The reflection of the wave continues in the small gap until the wave totally dissipates in the bubbly liquid. The sound field can be described in Eq. (3).

$$p(r,z,t) = A_0 D_s(r)\cdot(\cos(kz)\cdot\cosh(\alpha_f z) + j\sin(kz)\cdot sihh(\alpha_f))e^{j\omega t} \tag{3}$$

where p is sound pressure, k is the wave number and ω is the angular frequency of the wave. $D_s(r)$ is the surface amplitude distribution of the radiator [17]. Since the pressure along z axis is only studied here, the displacement D_s is independent of r. A_0 is the amplitude of the sound pressure at $r = 0$, which is described in Eq. (4).

$$A_0 = \frac{V_0\rho_0 c}{\sqrt{\sinh^2(\alpha_f L) + \sin^2(kL)}} \tag{4}$$

where V_0 is the surface vibration amplitude at $r = 0$. Notice that the speed of fluid in r direction is ignored in the equation. By substituting Eq. (4) into Eq. (3), the distribution of sound pressure along z axis in the gap is obtained.

The impacting force caused by cavitation bubbles is related not only to the sound field but also to the bubble dynamics. The dynamics of a spherical bubble in an infinite body of liquid can be described by the Rayleigh-Plesset equation [18]. In this paper, cavitation bubbles are confined in so small a gap that the bubbles in the collapsed phase are not spherical. Nevertheless, the Rayleigh-Plesset equation is still a valued method to roughly estimate the bubble size, which is described as

$$\mathrm{R}\frac{d^2R}{dt^2} + \frac{3}{2}\left(\frac{dR}{dt}\right)^2 = \frac{1}{\rho}\left(\mathrm{P}_0 - P_A\sin\omega t + \frac{2\sigma}{R} + \frac{4\mu}{R}\frac{dR}{dt} - P_v - \left(\mathrm{P}_0 + \frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3k}\right) \tag{5}$$

where ρ is the density of liquid, c the sound speed in liquid without cavitation, σ a surface tension coefficient, μ the viscosity coefficient, P_0 and P_v are the static pressure and vapor pressure respectively, k the polytropic exponent, P_A is the sound pressure within the bubble, which is assumed to be uniform. The sound speed and absorption coefficient in cavitation liquid are calculated by Eq. (1). According to Eq. (5), the change of the maximum radius (R_m) of the cavitation bubble along with the change of sound pressure is shown in Fig. 1. All the values of the physical parameters used in the model are shown in Table 1.

When it reaches the maximum size, the bubble begins to shrink because of the surrounding pressure. Then the bubble collapses in