NumericalStudy on Dynamic Evolution of a Dual-Frequency Driven Cavitation Bubble in Magnesium Alloy Melt

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Abstract: The enhancement and control of acoustic cavitation in metal preparation by dual-frequency ultrasonic have been verified experimentally. However, the research is still in infancy and the theoretical mechanism needs to be further explored. Therefore, the dynamic model of a dual-frequency driven cavitation bubble in magnesium alloy established for the first time. The effect of equilibrium radius, driving frequency, acoustic pressure amplitude and ratio were discussed in detail in the f_1-f_2 space. An excessively large equilibrium radius resulted in a long bubble collapse-time, and too small an equilibrium radius resulted in a low collapse strength. In the frequency domain of low-low or low-high frequency coupling, the cavitation bubble collapse strength was high and sensitive to variations in the driving frequency. At both driving frequencies above 100 kHz, the collapse strength reduced to a stable interval and no longer responded significantly to variations in frequency. Increasing the total acoustic pressure amplitude enhanced the synergistic effect between the two distinct driving frequencies. The collapse strength for equal driving frequencies was independent of the acoustic pressure ratio. For two distinct drive frequencies, increasing the acoustic pressure share at a lower frequency or decreasing the acoustic pressure share at a higher frequency increased the collapse strength. The analysis of bubble collapse time indicated that obtaining higher collapse strength often comes at the cost of a longer collapse time.

Keywords: Dual-frequency ultrasonic, Cavitation bubble, Dynamic evolution, Collapse strength

1 Introduction

In recent years, ultrasonic technology has received increasing attention in the field of solidification behavior regulation of metal melts. Dual-frequency ultrasonic has been applied in metal casting due to the excellent ability to refine microstructures[1-3].Although the effective control and enhancement of acoustic cavitation by dual-frequency or multi-frequency ultrasound have been experimentally verified, the study is still in its infancy. The universality needs to be improved, and the theoretical mechanisms need to be further explored. The cavitation dynamic is the most effective way to understand cavitation effects from a theoretical perspective.

In this paper, a dual-frequency driven cavitation bubble dynamic model is established based on the Rayleigh-Plesset equation. The dynamic evolution of cavitation bubble was systematically analyzed in a wide parameter range with AZ80 magnesium alloy melt chosen as a simulation system. The effects of cavitation nucleus equilibrium radius, driving frequency, acoustic pressure amplitude, and acoustic pressure ratio in cavitation strength are discussed in detail in the f_1-f_2 space. This is the first numerical analysis concerning on the cavitation bubble dynamic under dual-frequency driven in a metal melt.

2 Mathematical model

The motion equation of the cavitation bubble radius$R$under the action of the dual-frequency ultrasonic fieldwith various parameters can be expressed as follows:

$$R\left(\frac{d^2R}{dt^2}\right)+\frac{3}{2}\left(\frac{dR}{dt}\right)^2=\frac{1}{\rho}\left[\begin{array}{l}\left(P_0+\frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3K}-\frac{2\sigma}{R}-\frac{4\mu}{R}\left(\frac{dR}{dt}\right)-P_0+P_V\\+P_{A1}\sin(2\pi f_1 t)+P_{A2}\sin(2\pi f_2 t)\end{array}\right] \quad (1)$$

where ρ is the density of melt, P_0 is the hydrostatic pressure acting on the bubble wall, σ is the surface tension, R_0 is the initial radius, K is the polytropic exponent, μ is the liquid viscosity, P_V is the vapor pressure inside bubble,P_{A1} and P_{A2} represent the acoustic pressure amplitudeof the two ultrasounds, and f_1, f_2 represent the ultrasonic frequencies.

3 Result and discussion

3.1 Influence of equilibrium radius

The bubble radii increased hundreds of times within the microsecond time variation, implying that the cavitation bubble went through an extremely exaggerated expansion and contraction in the dual-frequency ultrasonic treatment. The calculations indicate that the cavitation bubbles with larger maximum radius have longer collapse times.

3.2 Influence of driving frequency

The simulation results show that a shorter collapse time can be obtained in the frequency domain of 30-500 kHz. In the frequency domain of low-low or low-high frequency coupling, the cavitation bubble collapse strength is high and sensitive to variations in the driving frequency. At both drive frequencies above 100 kHz, the collapse strength reduces to a stable interval and no longer responds significantly to variations in frequency.

3.3Influence of acoustic pressure amplitude

Larger acoustic pressure amplitudes created more intense bubble oscillation, but also caused the bubble to collapse more slowly.The projection of the collapse strength on the f_1-f_2 plane indicates that high collapse strength always occurs on the low-low and low-high coupling frequency sides in the frequency domain.Furthermore,increasing the acoustic pressure amplitude enhances the synergistic effect between two distinct driving frequencies, and thus increases the cavitation intensity. In contrast, the enhancement does not seem to exist between equal driving frequencies by increasing the acoustic pressure amplitude.

For equal driving frequencies, the collapse strength is independent of the acoustic pressure ratio, but is related to the driving frequency. For distinct driving frequencies, the collapse strength is closely related to the acoustic pressure ratio. Increasing the acoustic pressure ratio at a lower frequency or decreasing the acoustic pressure ratio at a higher frequency will significantly enhance the collapse strength under dual-frequency driven.

4 Conclusion

In this paper, based on the derived Rayleigh-Plesset equation, a cavitation bubble dynamics model under dual-frequency driven is established. The numerical solution is obtained by the 4th-order Runge-Kutta method to clarify the dynamic evolution of a single cavitation bubble radius in the molten medium. The collapse strength was defined based on the cavitation bubble expansion ratio and the influencing factors such as the equilibrium radius of the cavitation nucleus, the driving frequency, and the acoustic pressure amplitude were investigated in the f_1-f_2 space.

The cavitation bubble goes through several exaggerated and irregular expansion-contractions under dual-frequency driven. The bubble radius increases hundreds of times in microseconds. The equilibrium radius of the initial cavitation nucleus present in the liquid is crucial to the cavitation effect. Too large an equilibrium radius leads to a long bubble collapse-time; too small an equilibrium radius results in a low collapse strength. Therefore, there is an optimum interval for the equilibrium radius size of the cavitation nucleus that favors the cavitation efficiency, which is related to the liquid physical properties and the acoustic driving parameters. The driving frequency is also critical for the cavitation effect. In the frequency domain of low-low or low-high frequency coupling, the cavitation bubble collapse strength is high and sensitive to variations in the driving frequency. At both driving frequencies above 100 kHz, the collapse strength reduces to a stable interval and no longer responds significantly to variations in frequency. Increasing the total acoustic pressure amplitude will enhance the synergistic effect between the two distinct driving frequencies. The collapse strength for equal driving frequencies is independent of the acoustic pressure ratio, but the collapse strength for distinct driving frequencies is closely related to the acoustic pressure ratio. Increasing the acoustic pressure share at a lower frequency or decreasing the acoustic pressure share at a higher frequency can effectively increase the collapse strength. The analysis of bubble collapse-time shows that obtaining higher collapse strength often comes at the cost of a longer collapse-time.

The pursuit of the highest collapse strength is not always an ultimate goal. For ultrasonic treatment of magnesium alloy melt, shorter cavitation bubble collapse-time and higher collapse strengths are desired. Therefore, the optimal cavitation effect is always obtained after a comprehensive consideration of collapse strength and collapse time. In addition, the dynamic evolution of a single cavitation bubble existing inside a cavitation cloud is necessarily affected by the pressure released by the surrounding bubble clusters. In the present work, the phenomenon of multiple cavitation bubbles is not considered. As a final remark, an exhaustive analysis of the cavitation bubble dynamic evolution or bubble-collapse modeling requires orders of magnitude higher computational resources.

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