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Numerical and experimental studies about the effect of acoustic streaming on ultrasonic processing of metal matrix nanocomposites (MMNCs)☆

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ABSTRACT

Acoustic streaming is a non-linear physical effect which can assist in effective distribution of nanomaterials in a liquid medium subjected to ultrasonic processing. In this study, a time-dependent non-linear computational model was developed to study the effect of various geometrical configurations of the ultrasonic processing cell on the evolution of acoustic streaming flow. Three different geometrical configurations of a flat-bottomed cylindrical processing cell were analyzed for this study. The most well-developed flow pattern is obtained for the geometrical configuration providing the largest acoustic cavitation zone size. Validation of the computational model was performed by two separate experiments – a sedimentation study and processing of a metal matrix nanocomposite (MMNC) composed of an aluminum alloy mixed with carbon nanofibers (CNFs) and silicon carbide (SiC) microparticles. CNFs sonicated in water using the optimum parameters showed the most stable dispersion after 43 h of observation. Microstructural analysis of a cast MMNC subjected to ultrasonic processing with the optimum parameters showed the effect of acoustic streaming in achieving more uniform distribution of solidified phases along with nanomaterials within the matrix compared to a mechanically stirred sample. Computational analysis showed that irregular bottom shapes of the processing cell significantly influence the acoustic cavitation and streaming flow patterns. These studies lay the groundwork for future research into optimizing the shape of the processing cell for scaling up ultrasonication to process larger volumes of liquid media.

1. Introduction

The acoustic streaming effect in ultrasonic liquid processing can be considered as fluid flow induced by the viscous attenuation of the energy of acoustic wave in the bulk of the liquid – which is also known as the Eckart mode of streaming [1]. The viscous attenuation decreases the pressure amplitude of the acoustic wave along the wave propagation direction. The rate of acoustic energy absorption by the fluid is proportional to the square of the acoustic wave frequency, as described by the Stoke's law of attenuation. The acoustic energy loss induces a steady flux of momentum, which forms a fluid jet in the direction of wave propagation. In the confined regions of the ultrasonic processing cell, the streaming flow also has a backflow component. [1,2].

Experimental characterization of acoustic streaming in ultrasonic processing of liquid media has been performed using laser Doppler velocimetry (LDV) [3,4] and particle image velocimetry (PIV) [5,6] to determine flow velocities using dispersed tracer particles. However, the use of optical visualization techniques is limited to processing of transparent media. For applications involving ultrasonic processing of metal melts, tools for experimental characterization are yet very limited. Numerical modeling of the non-linear physical phenomena associated with ultrasonic processing would provide a viable alternative for characterization of fluid behavior in the ultrasonic pressure field.

For numerical modeling of acoustic streaming flow, direct transient solution of the Navier-Stokes equation has been typically used by researchers, which is easier to adapt for arbitrary geometries compared to using traditional perturbation theory [7,8]. Moudjed performed a scaling analysis of acoustic streaming flow, and explained that apart from acoustic attenuation, consideration of acoustic diffraction is essential to fully resolve the effects of acoustic

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streaming in any non-linear numerical model [9]. Trujillo showed that for power levels greater than 50W, the acoustic momentum rate is converted into acoustic streaming flow in close vicinity to the acoustic radiation source, implying that the streaming can be predicted as a function of the acoustic power [10]. Sajjadi's computational model for ultrasonic processing using a range of liquid level heights showed that higher acoustic streaming velocities are observed in regions closer to the ultrasonic transducer probe tip, with lower velocities occur near the side walls of the vessel [11]. Other computational approaches regarding acoustic streaming involved use of dynamic mesh models [12], estimation of acoustic radiation force densities [13,14] and incorporation of acoustic fountain shape into computational domain [15].

Ultrasonic processing has been widely applied to the production of MMNCs due to its superior effectiveness in dispersing nanoparticles compared to other conventional means such as mechanical stirring. During ultrasonic processing of particle-reinforced metal matrix composites, the particles can be transferred across long distances in the melt when subjected to acoustic streaming effects. Acoustic streaming induced spiral vortices generated in a fluid medium containing particles assists in vigorous mixing and homogenization of particles. The homogenization effect caused by acoustic streaming can thus influence the micro and macro-distribution of the particle in the solidified composite. In a study of isothermal ultrasonic processing of Zn-Al composites reinforced with SiC microparticles, Xu showed that clustering of SiC particles was closely related to the acoustic streaming pattern and the interactions of the particles with both the processing vessel and the melt [16]. Gao et al. showed that in the ultrasonic processing of Al-4.5Cu melts with 5 vol% TiB_2 particulates, acoustic cavitation effects helped in breaking agglomeration of particles as small as 100 nm, while acoustic streaming assisted in achieving dispersions of particles smaller than 400 nm along the grain boundaries in the matrix. The vortices generated by acoustic streaming are 5–10 times faster than the heat convection in the melt, which assists in enhanced heat transfer and intense acceleration of the solute throughout the bulk melt [17]. Kai et al. showed that uniform dispersion of ZrB_2 nanoparticles in 2024 aluminum alloy induced by acoustic streaming resulted in enhanced mechanical strength and elongation of the solidified composite. The uniformity of nanoparticle dispersion was shown to be beneficial for matrix grain structure refinement during solidification, due to enhanced heterogeneous nucleation effects [18,19].

Although the non-linear effects of acoustic cavitation and acoustic streaming have been extensively studied, there remains a gap in scientific literature regarding the influence of the geometrical configuration of the ultrasonic processing cell on the development of these phenomena. The gaps in knowledge need to be addressed in order to pave the way for scaling up ultrasonic processing in applications such as high volume production of MMNCs. In our previous work, we developed a non-linear computational model to resolve the acoustic pressure field inside an ultrasonic processing cell. A systematic study was conducted to estimate the size of the acoustic cavitation zone in relation to a set of dimensionless geometrical parameters [20]. In this work, the model has been extended to study the effect of the geometrical parameters on the development of acoustic streaming flow. The results of the computational model were validated using an experiment to observe the sedimentation of ultrasonically processed CNFs in water over a period of 43 h. The effectiveness of using the best set of determined geometrical parameters for the ultrasonic processing of an aluminum alloy based MMNC was then studied using microstructural analysis. An additional study was performed to study the effect of the shape of the bottom surface of the ultrasonic processing cell on acoustic cavitation and acoustic streaming.

2. Numerical modeling

The acoustic streaming effect in an ultrasonic processing cell was modeled using the non-linear Helmholtz equation [21]. The equation accounts for the attenuation of the acoustic wave propagation due to the viscous properties of the fluid medium. The equation is given in Eq. (1):

$$\nabla\left(\frac{1}{\rho_c}\nabla P\right)-\frac{\omega^2}{\rho_c c_c^2}\frac{\partial^2 P}{\partial t^2}=0 \tag{1}$$

where, P is the acoustic pressure, t is the time and ω is the angular frequency of the ultrasonic wave. ρ_c is the complex density and c_c is the complex sound speed [22], as defined by the Eqs. (2) and (3):

$$\rho_c=\rho\left(\frac{c}{c_c}\right)^2 \tag{2}$$

$$c_c=c\left\{1+\frac{i\omega}{\rho c^2}\left(4\eta/3+\mu_b\right)\right\}^{1/2} \tag{3}$$

where, η is the dynamic viscosity and μ_b is the bulk viscosity of the liquid medium. The attenuation losses of the acoustic pressure wave of frequency f propagating at a speed c in a liquid medium of density ρ can be obtained by calculating the attenuation coefficient α [23], which is used to calculate the acoustic radiation force, F generated by the change in momentum due to the propagation of ultrasonic waves in the liquid [24]. The values of α and F are obtained using Eqs. (4) and (5):

$$\alpha=\frac{8\eta\pi^2 f^2}{3\rho c^3} \tag{4}$$

$$F=\frac{2\alpha|P|^2}{\rho c^2} \tag{5}$$

where, $|P|$ is the instantaneous pressure at a given point inside the ultrasonic processing cell. The acoustic radiation force is calculated at each instant in every location and used in the incompressible Navier-Stokes equation [25], shown in Eq. (6). The velocity profile of the acoustic streaming flow is obtained by solving Eq. (6) and the continuity equation given by Eq. (7):

$$\rho\frac{\partial \mathbf{u}}{\partial t}+\rho\mathbf{u}.\nabla\mathbf{u}=-\nabla P+\eta\nabla^2\mathbf{u}+F \tag{6}$$

$$\nabla\mathbf{u}=0 \tag{7}$$

Considering that the acoustic cavitation zone during ultrasonic processing is concentrated in the region close to the probe tip, an unstructured mesh was used for discretization of the finite element model. A fine mesh size with a node length smaller than the wavelength of the ultrasonic wave was used in the region around the probe tip, while a progressively coarser mesh size was used in the rest of the model.

2.1. Modeling geometry and boundary conditions

An axisymmetric 2D section of the ultrasonic processing cell with an ultrasonic probe was used as the modeling geometry. An illustration of the ultrasonic processing cell is shown in Fig. 1, which is a cylinder with a rectangular cross-section. The ultrasonic probe of diameter D_P is immersed at a depth d in the ultrasonic processing cell of diameter D. The height of the liquid inside the cell is H, which also accounts for the rise in the height of liquid level upon immersion of the probe. The wall thickness of the ultrasonic processing cell was 3 mm. Water was considered as the fluid medium. Borosilicate glass was used as the material for the ultrasonic processing cell in the model. The ultrasound frequency used was 20,000 Hz.

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