Geometrical Effect on Ultrasonic Processing for Metal Matrix Nanocomposites (MMNCs)

Department of Mechanical Engineering, Clemson University
Master of Science (MS) degree (thesis option) in Mechanical Engineering

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Overview

Metal matrix nanocomposites have shown great promise in improving the material properties with considerable weight reduction. One promising way to integrate nanomaterials into a metal matrix would be a 2-step processing method, which consists of a pre-processing and a primary processing. A master nanocomposite from the pre-processing is subjected to ultrasonic processing in the primary processing for further distribution and dispersion of nanomaterials. However, there is the size limit of the ultrasonic cavitation zone caused by a geometry of crucible during the ultrasonic processing. Studying the geometrical effects on the cavitation zone will help us understand the relationship between processing parameters and effectiveness of the ultrasonic processing. In this study we employ the finite element method for simulating the acoustic streaming flow based on the acoustic pressure field during the ultrasonic processing to investigate the geometrical effect. The results show that there are significant variations in the cavitation zone caused by a change of the crucible diameter and the immersion depth of the ultrasonic probe. The reflections from the insides walls and bottom surface of the crucible generate a constructive or destructive interference of the ultrasound waves, resulting in the size change of the cavitation zone. An experimental validation has been also accomplished using Al-Si-Cu-Mg alloy with carbon nanofibers. With appropriately selected processing parameters, the area of micro pores in the MMNC was significantly decreased by 50% and a deviation of the hardness was also decreased by 46% which was attributed to further dispersion and distribution of the carbon nanofibers.

Motivation

- Nonlinear effects of ultrasonic processing for further dispersion and distribution of nanomaterials in 2-step processing method for manufacturing MMNCs
  - ***Ultrasonic cavitation***: formation of gas bubbles above a certain cavitation threshold pressure
  - ***Acoustic streaming***: flow caused by attenuation of the acoustic pressure field
- Constructive or destructive interference of the ultrasonic waves caused by a geometry of crucible and the immersion depth of the ultrasonic probe
- Experimental difficulties for the measurements of the nonlinear effects
- Modeling of the acoustic streaming flow based on the cavitation zone variation for understanding the relationship between processing parameters and effectiveness of the ultrasonic processing

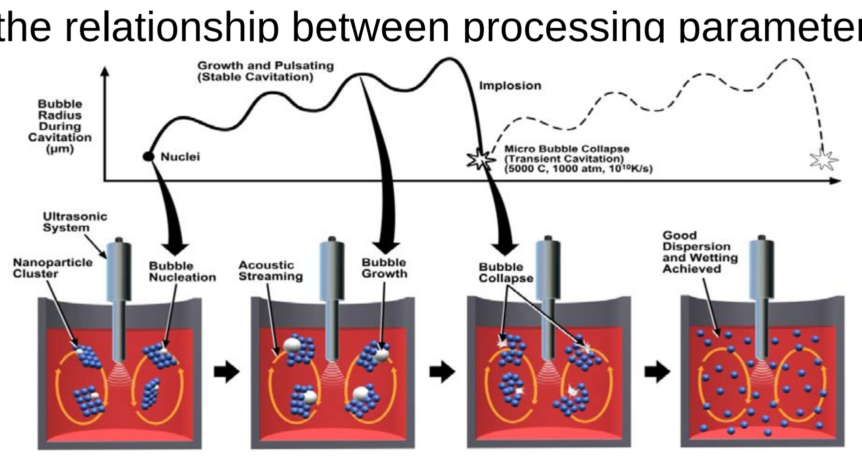


Fig.1 Nonlinear effects of ultrasonic processing

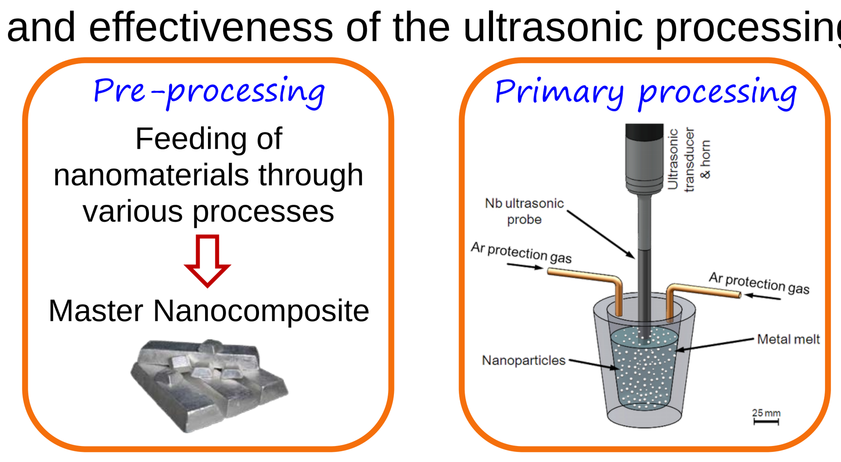


Fig. 2 2-step processing method

Progress

- **Modeling of acoustic pressure field:** with 2D axisymmetric nonlinear harmonic acoustic FEM model with temperature-dependent properites

$$\nabla\left(\frac{1}{\rho_c}\nabla \boldsymbol{P}\right)+\frac{\boldsymbol{\omega}^2}{\rho_c c_c{}^2}.\boldsymbol{P}=0$$

Where, ρ_c *is the complex density,* c_c *is complex sound speed,* ω *is the angular frequency & P is the pressure*

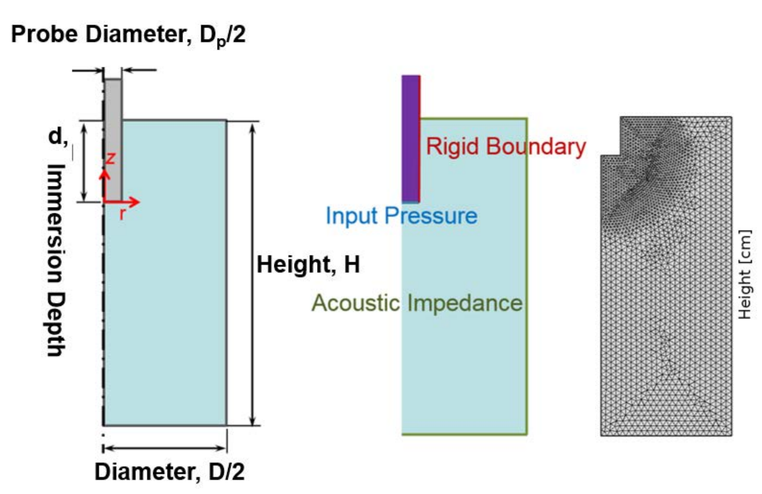


Fig.3 FEM Modeling

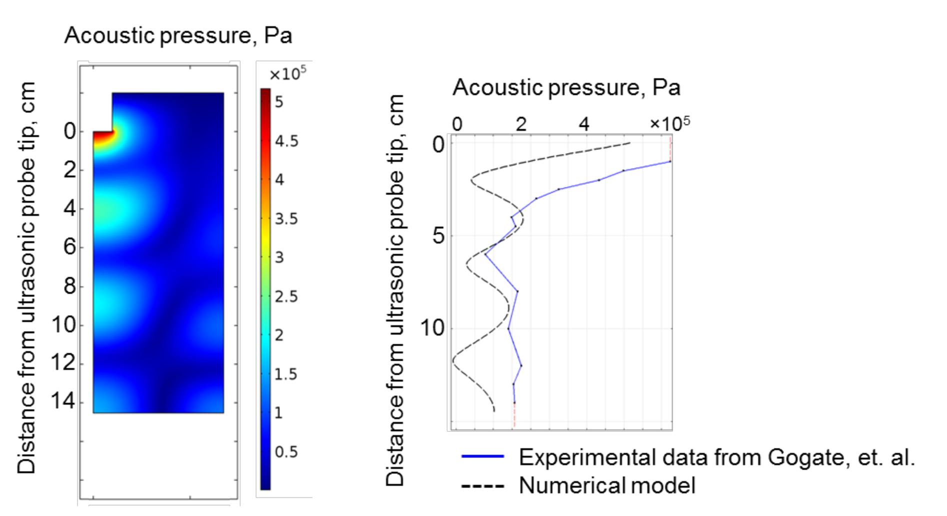
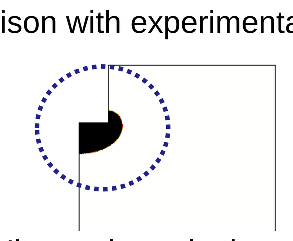


Fig.4 Acoustic pressure field and its comparison with experimental data

- **Quantifying of cavitation zone:** The area of the region where the acoustic pressure is above the cavitation threshold is measure and then converted into the equivalent diameter (D_{eq})



Ultrasonic cavitation zone

- **Variable selection for parametric analysis:** For a melt volume of 50 ml and probe diameter of 12.7 mm, diameter of crucible (**D**) and immersion depth of probe (**d**)
- **Modeling of acoustic streaming flow:** Using the Navier-Stokes equation for flow field coupled with the nonlinear acoustic field eqaution
- **Experimental validation:** Using aluminum alloy A4000 (Al-11.5 Si-4.25 Cu-0.65 Mg) with carbon nanofibers (diameter:150nm, length:6 μm) and SiC micro particles (diameter: 5.5 μm)

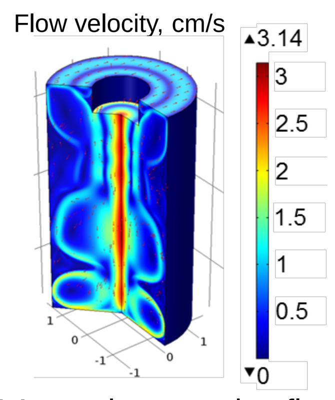


Fig.5 Acoustic streaming flow after 0.9 seconds

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Intellectual Merit & Broader Impacts

- This study significantly advances the scientific knowledge on the nonlinearity of the ultrasonic processing for the nanomaterial dispersion and distribution for manufacturing MMNCs.
- This study helps us understand the effects of crucible geometry and processing parameters on the ultrasonic cavitation zone and the acoustic streaming flow.
- The research will empower a general guideline to select suitable crucible geometries as effective processing parameters to achieve high performance of alloys for widespread applications.
- The success of this research will enable the scalable manufacturing of MMNCs using the 2-step processing method for the practical applications with a large volume.
  - ***Aviation***: to manufacture components which demand tremendous weight constraints, high stiffness and strength
  - ***Automotive****:* for components that require high wear resistance and thermal conductivity

Research Plan

- To develop a finite element model to resolve the nonlinear acoustic pressure field
- To identify and quantify the ultrasonic cavitation zone
- To perform parametric analysis of geometrical parameters (diameter and immersion depth)
- To resolve the acoustic streaming flow with a time-harmonic nonlinear acoustic model
- To experimentally validate the model (mechanical properties, microstructure analysis, porosity)
- To modify the FEM model based on the experimental validation results

Illustrative Figures

- **The effect of crucible diameter (D) and immersion depth (d) on the equivalent diameter (D_{eq})**

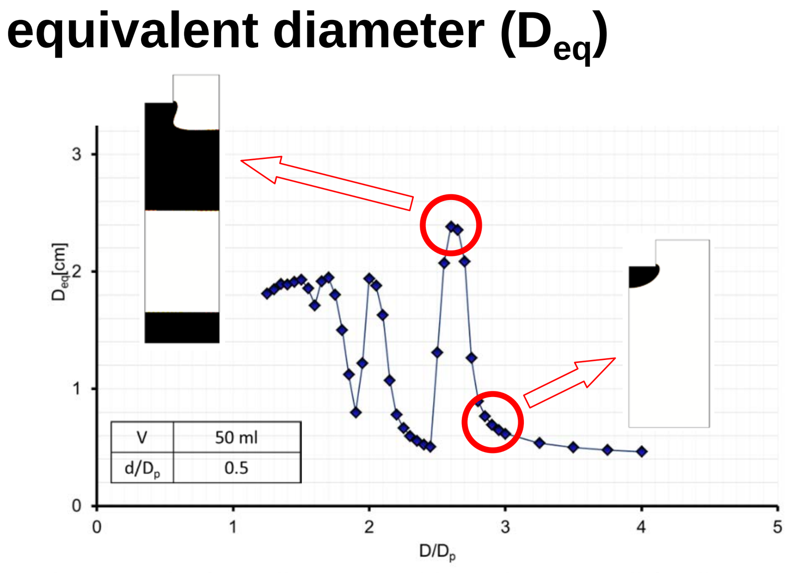

Fig.6 Equivalent diameter with various crucible diameter

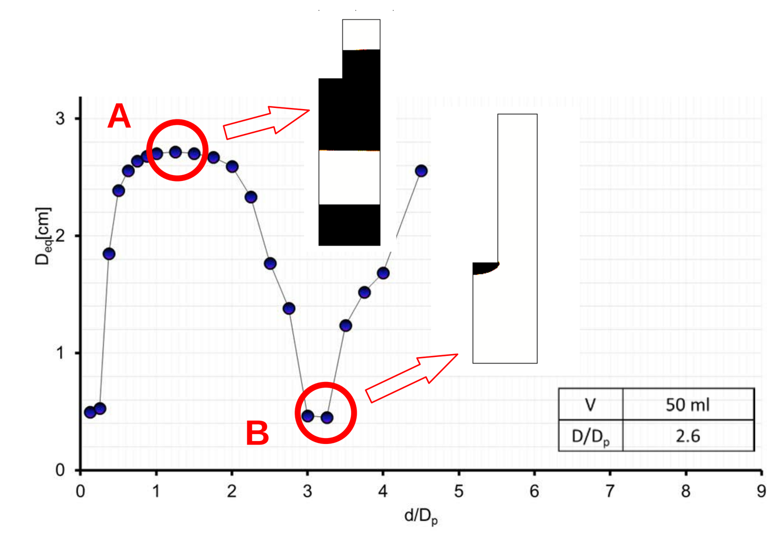

Fig.7 Equivalent diameter with various immersion depth

- **Acoustic streaming flows with different immersion depths**

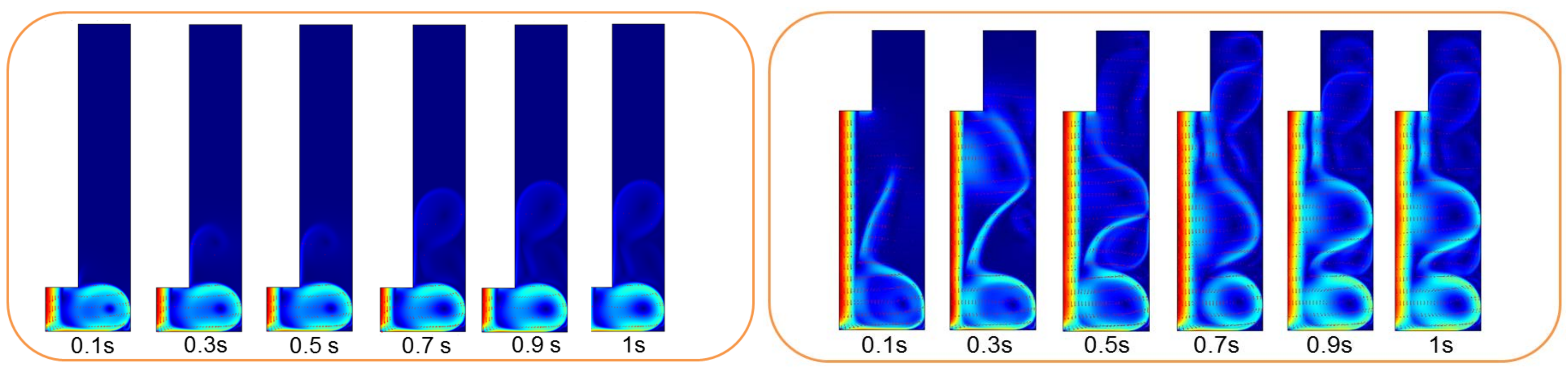

Fig.8 Evolution of acoustic streaming flow in **A** and **B** from 0.1 seconds to 1 seconds

- **Experimental setup**

Fig.9 Experimental Setup

- **Carbon nanofibers and SiC microparticles**

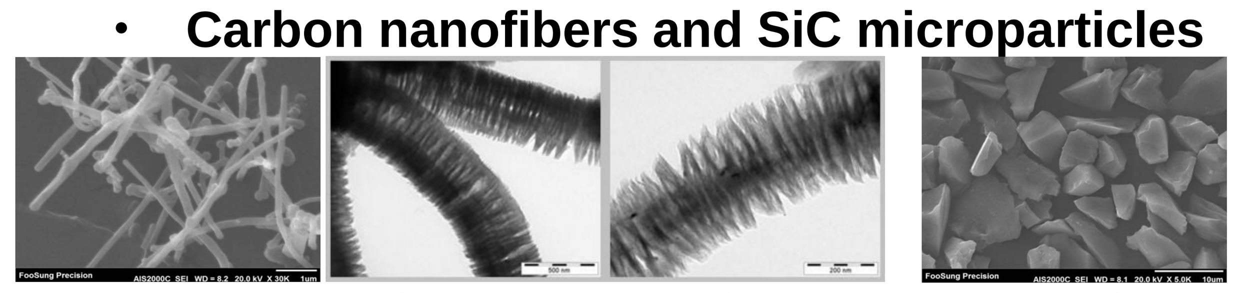

Fig.10 Carbon nanofiber with various magnification and SiC micro particles

- **Al-11.5Si-4.25Cu-0.65Mg MMNCs**

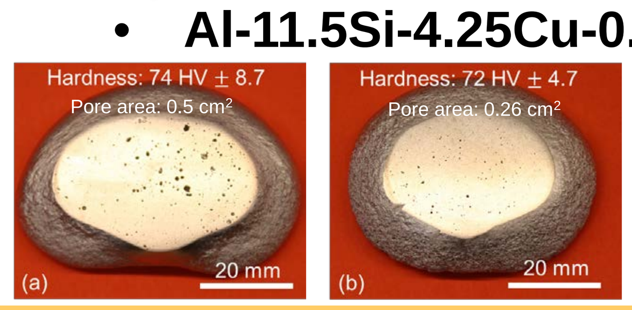

Fig.11 Aluminum-based MMNCs manufactured using 2-step processing:
(a) mechanically stirred for 30 minutes
(b) ultrasonic processed with parameters selected from numerical simulation results for 30 minutes

Conclusions

- A nonlinear acoustic FEM model is developed for the acoustic pressure field using temperature-dependent properties, which is used for simulating a transient acoustic streaming flow.
- The results of the parametric analysis are used to identify the geometric configurations and the immersion depth for the maximum ultrasonic cavitation zone with a current specific size of probe and liquid volume.
- With appropriately selected processing parameters, the area of micro pores in the MMNC was significantly decreased by 50% compared with MMNC manufactured through 2-step processing method with mechanical stirring.
- A deviation of the hardness was also decreased by 46% which was attributed to further dispersion and distribution of the carbon nanofibers.

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