Applied Acoustics 103 (2016) 226–231

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

An experimental and modeling investigation of aluminum-based alloys and nanocomposites processed by ultrasonic cavitation processing

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ARTICLE INFO

Article history:
Received 3 February 2015
Received in revised form 17 July 2015
Accepted 27 July 2015
Available online 31 August 2015

Keywords:
Ultrasonic stirring
Cavitation
A356 alloy
Nanocomposites
Microstructure and mechanical properties
Numerical modeling of ceramic nanoparticle dispersion

ABSTRACT

Some recent studies are showing that the microstructure and mechanical properties of manufactured components can be significantly improved when ceramic nanoparticles are used as reinforcement to form a metal-matrix-nano-composite (MMNC). During the fabrication of MMNCs, ultrasonic cavitation processing plays an important role in refining microstructure, dispersing nanoparticles and breaking up clusters of nanoparticles.

In the present study, aluminum A356 alloy and Al_2O_3/SiC nanoparticles are used as the matrix alloy and the reinforcements, respectively. Nanoparticles are injected into the molten alloy and dispersed by ultrasonic cavitation and acoustic streaming. The microstructure and mechanical properties of the cast nanocomposites have been investigated in detail.

1. Introduction

Aluminum matrix nanocomposites have the potential to offer outstanding properties, including low density, high specific strength, high specific stiffness, excellent wear resistance and controllable expansion coefficient, which make them attractive for numerous applications in aerospace, automobile, and military industries field [1–10]. As shown in literatures [11,12], it is beneficial to use nano-sized ceramic particles to fabricate metal matrix nano-composites (MMNCs) since similar ductility and higher strength with the metal matrix can be achieved. Currently, there are several fabrication methods of MMNCs, including mechanical alloying with high energy milling [13], ball milling [14], nano-sintering [15], spray deposition, electrical plating, sol–gel synthesis, laser deposition, *etc*. The mixing of nano-sized ceramic particles is normally lengthy, expensive, and energy consuming.

Ultrasonic Stirring Technology (UST) has been extensively used in purifying, degassing, and refinement of metallic melt [16–20], mainly because introducing the ultrasonic energy into a liquid will induce nonlinear effects such as cavitation and acoustic streaming.

Al_2O_3 and SiC are widely used as reinforcement particles due to their relatively good thermal and chemical stability. In this article, the effects of the ultrasonically dispersed Al_2O_3 and SiC nanoparticles on the microstructure and mechanical properties of A356 nanocomposites are studied in detail.

The dispersing and de-agglomeration of nanoparticles into liquids is an important application of ultrasonic devices. If powders are wetted, the nanoparticles build agglomerates and are held together by attraction forces of various physical and chemical nature, including van der Waals forces and liquid surface tension. The attraction forces must be overcome in order to de-agglomerate and disperse the particles into liquid media. An uniform dispersion and de-agglomeration is important to use the full potential of the particles. Nanoparticles offer extraordinary characteristics, which can only be exploited in highly uniform dispersed state.

The application of stress generated by ultrasonic cavitation breaks the particle agglomerates apart. Also, liquid is pressed between the particles. Dispersion by ultrasonic is a consequence of micro-turbulences caused by fluctuation of pressure and cavitation. Ultrasonic cavitation is very effective in breaking agglomerates, aggregates and even primaries. Small-size transient domains created by ultrasonic cavitation could reach very high temperatures and pressures as well as extremely high heating and cooling rates. The shock force that takes place during ultrasonic cavitation processing coupled with local high temperatures can break the nanoparticle clusters and clean the surface of the particles. Furthermore, ultrasonic vibration can improve the wettability between the reinforced nanoparticles and the metal matrix [21–23], which will assist to distribute the nanoparticles more uni-

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http://dx.doi.org/10.1016/j.apacoust.2015.07.016
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formly into the metal matrix. Ultrasonic cavitation in liquids causes high speed liquid jets of up to 1000 km/h (approx. 600 mph). Such jets press liquid at high pressure between the particles and separate them from each other [24].

2. Experimental approach

Aluminum alloy A356 is selected as the metallic matrix. The ceramic nanoparticles used in this study are β-SiC (spherical shape, average diameter of about 50 nm) and Al_2O_3 (spherical shape, average diameter of 20 nm).

The ultrasonic processing system used in this study is illustrated in Fig. 1. The main parameters of the ultrasonic equipment are as following: maximum power, $P = 2.4$ kW and frequency, $f = 18$ kHz. An induction furnace with a capacity of 2.7 kg was used to melt alloy. After the alloy is melted, the Nb ultrasonic probe is inserted to about 50 mm beneath the melt surface to perform ultrasonic stirring at 1.75 kW and 18 kHz frequency. 1 wt.% of nanoparticles (Al_2O_3 or SiC) are injected into the cavitation area. The molten pool is protected by Argon gas atmosphere. The experiments are repeated several times for statistical interpretation of the results.

Experiments applying UST treatment during solidification are performed to better understand the effects of UST. The comparison experiment is done by melting A356 alloy and turning off the furnace to let the molten metal solidify. The other experiment is done by melting the A356 alloy and turning off furnace, and then during solidification, treating the molten alloy with UST.

3. Modeling approach

The geometry of the model is shown in Fig. 2. The ultrasonic probe has a diameter of 40 mm. The liquid aluminum is A356. The SiC and Al_2O_3 are treated as inert-particles. The mass flow rate of the nanoparticles is 0.014 kg/s. Thus, 1.0 wt.% of nanoparticles can be injected at about 20 mm above the bottom of the furnace for 1.0 s.

The multiphase CFD model is able to account for turbulent fluid flow, heat transfer, solidification and the complex interaction between the molten alloy and nanoparticles by using the ANSYS Fluent DDPM and κ–ω turbulence model. The CFD mode is described in detail in [25,26].

The solution procedure is presented in the following paragraph. The nanoparticles are injected at every fluid flow time step with a mass flow rate of 0.014 kg/s in the first second. Particles are tracked at every time step after the fluid velocity field is solved. Because of the low volume fraction of the discrete phase, one-way coupling is employed, which neglects the effect of the discrete phase on the fluid turbulence. The boundary conditions used in the simulations are described in the following paragraph. After

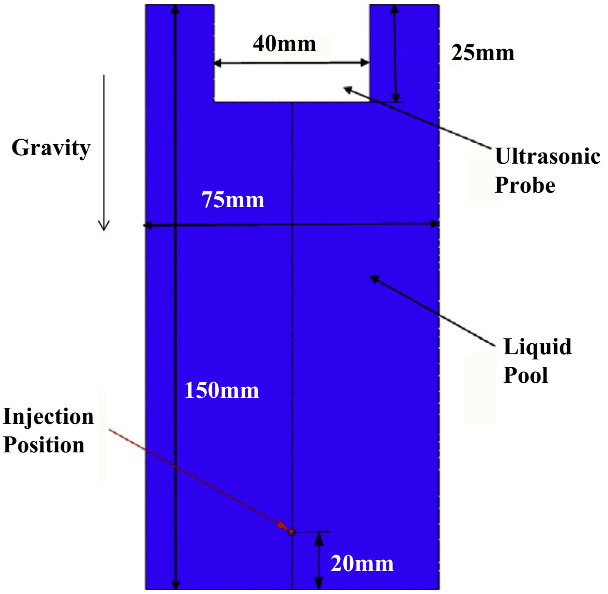

Fig. 2. Geometry of model.

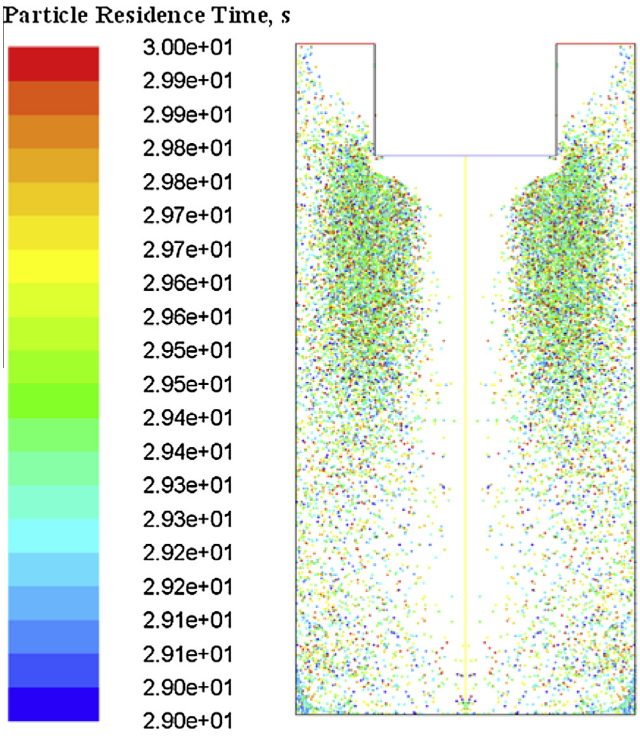

Fig. 3. Predicted distribution of nanoparticles after 30 s in an A356 melt.

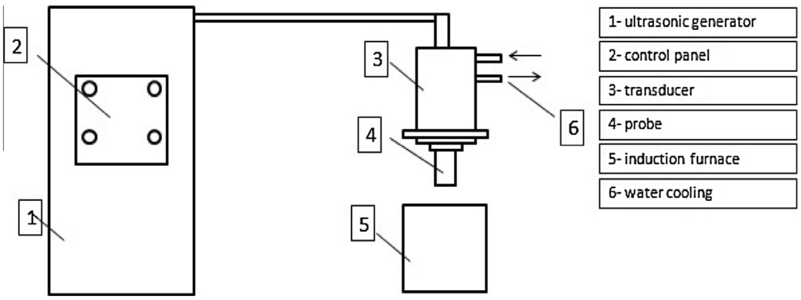

Fig. 1. A schematic of the UST and induction furnace equipment.