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Fabrication of Light Weight Metal Matrix Nanocomposites using Ultrasonic Cavitation Process: A State of Review

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Abstract. Fabrication of nanocomposites is a highly challenging task because of the particles need to be disseminated across the molten liquid. The broad surface area, poor wettability. Homogeneous dispersion is tough in traditional stirring methods leads to cluster and agglomeration formation in high viscous molten metals. In such attempts, the ultrasonic vibration process exhibits the better dispersion and distribution of nanocomposites with enhanced material properties as compared to other fabrication processes. This paper deals with the fabrication process, probe design and effective process parameters of sonication process to the uniform dispersion of nanoparticles.

Introduction

From the last two decades, researchers are aiming for aluminum and magnesium…etc. because of material high strength to weight ratio value. The traditional fabrication methods for lightweight metal matrix composites involve mechanical stirring, powder metallurgy, squeeze casting and semisolid stirring. In recent years the ceramic particles have been scaled up to nano-size such as nano Al_2O_3, SiC, B_4C, BN, TiC, TiB_2..etc. have been used to reinforcements to form metal matrix nanocomposite (MMNC). There are several ways to produce MMNCs, the popular methods being powder metallurgy and liquid casting route respectively. The casting process is a liquid phase method to manufacture a component with highly complex in shapes. But getting uniform dispersion and distribution of ceramic particle in a metallic liquid is highly difficult due to its poor wettability, high viscosity as well as a huge ratio of surface to volume.

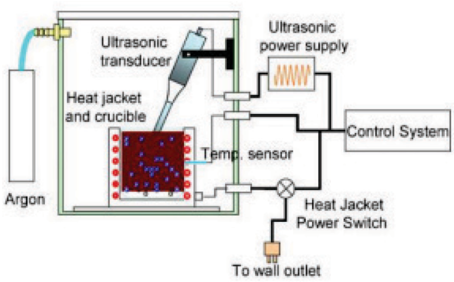

Figure 1. Schematic view of ultrasonic cavitation process set-up

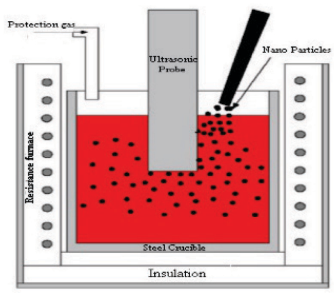

Figure 2. Experimental set-up for fabricating nanocomposites.[11]

With fabrication process, the nano-sized particles creates the problems like clusters and agglomerations during the incorporating, but new sonication and high shearing methods were initiated to help the dispersion, degassing and de-agglomeration of fine as well as nano-sized particles in aluminium and other alloys. Recently some researchers have proven that the nanocomposite which was treated by the ultrasonic cavitation machine is exhibits very good results. Dispersion and distribution of nano-ceramic particles may be accomplished with mechanical stirring. The traditional stirring methods find it very tough to produce nanocomposites with ultra-fine particles inclusion due to their large specific areas.For such cases Li et al [9], Lan et al [8], and Yang et al [10] introduced a very successful technique to produce nanocomposites by distributing and dispersion of ultra-fine reinforcement particles in liquid metal using ultrasonic vibrational technique. In this technique, a lot of bubbles are created in liquid metal during the positive frequency and made to collapses in the negative frequency. This bubble collapse creates the ultimate pressure and temperature, resulting in de-agglomeration, cluster disturbance and spreads into the molten liquid. Fig. 2 shows a part of the schematic diagram of the equipment for ultrasonic cavitation based solidification process. [11, 24]

The experimental setup consists of a heat furnace with resistance for melting base metal, a gas protection system,a feeding mechanism with nanoparticles and Ultrasonic process system. The equipment has mild steel crucible of 127mm height and 114mm inside diameter (ID), which is used for melting base metal matrix. In ultrasonic process, a probe, which is made up of niobium C-103 alloy and titanium alloy, is used due to its high-temperature resistance property and because it does not react with molten liquid during the sonication process, to produce maximum 4kw power output and 17.5kHz frequency for melting process; the niobium probe is 39cm in length and 35mm in diameter, is dipped into the melt pool and in case of titanium alloy probe 115mm in length and 20mm in diameter to achieve effective sonication. The ultrasonic processing melt temperature is about 700-800 degree centigrade. This process is performed after adding pre-heating ultra-fine (nano) ceramic particles through steel tube into the matrix melt and the process can refine grain size of matrix material significantly and disperse as well as distribute homogeneously after finishing the ultrasonic test in material matrix melt pool; the processed liquid is than poured into a preheated (about 400^0C) permanent steel mold cavity to cast it.

The Effect of Ultrasonication

The treatment of ultrasonic for liquid metals is a dynamic, cost-effective and environmentally friendly process. Since the 1950s, the ultrasonic treatment (UST) has been implemented and it shows the ultrasound application during the solidification process of liquid metals.[12] This technique is introduced to produce a broad area of material matrix nanocomposites. In the current UST process, the strongest non-linear effects are generated in molten metal alloy by great intensity of ultrasonic waves, namely, acoustic streaming and transient cavitation. Additionally, the transient miniaturized scale problem areas with a temperature of around 5000 k, and pressure of above 1000 atm can be settled. The solid effect of combination with confined elevated temperature can clear the molecule surface, break nanoparticles groups, enhance their wettability and circulate nanoparticles inside the molten metal. Ultrasonic probe vibrations carried out at the time of the liquid as well as solidifying liquid metal results in the follows:

I. Reduction in porosity by degassing
II. Particles and grain refinement of primary phase
III. Grain duplication because of dendrite fragmentation and increase in nucleation because of initiation of substrates through wetting.
IV. During the debacle of cavitation bubbles, large acoustic pressures are exerted which cause reduction in segregation and agglomeration.
V. Dispersing as well as distributing of immiscible or solid form through natural process as well as acoustic micro-streaming

The dispersion of nanoparticles

It is very tricky to circulate nano-sized particles in a liquid medium because of their higher surface to weight ratio as well as poor wettability; these nanoparticles form clusters because of their surface property when mixed with a liquid medium or when they are exposed to the atmosphere. So, the new fabrication method gets rid of nanoclusters to get uniform distribution. In this process, uniform distribution and breaking of nanoclusters taking place because of acoustic streaming phenomena.

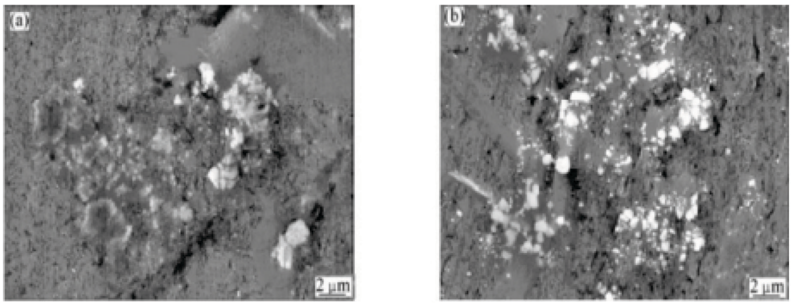

Figure 3. SEM image (a) Without high-energy ultrasonic field;(b) With high-energy ultrasonic field[22]

Acoustic streaming

[8] Contrasted with conventional energy sources, the ultrasonic illumination stipulates fundamentally odd response conditions (a brief span of too many high temperatures and in addition pressures in fluids) that can't be acknowledged by different strategies strikingly, and such exceptional situations are not obtained in a straightforward fashion from ultrasound vibration. Acoustic wavelengths are significantly greater than sub-atomic measurements. In this way, no immediate, atomic level association among ultrasound and additionally, the compound species, happens. Rather, acoustic cavitation (i.e., the development, enlargement as well as the implosive fail of air bubbles in fluids) is determined through the chemical impacts of ultrasound by high-intensity ultrasound represents. At the point when fluids are illuminated through ultrasound, the substituting broad and compressive acoustic waves produce bubbles (i.e., cavities). The faltering air pockets can increment ultrasonic energy efficiently while developing a specific range in microns (μm). Under correct circumstances, an air pocket (bubbles) can increase and collapse subsequently, discharging the moving energy saved in the rise inside a bubble within fraction of seconds (with a cooling as well as the heating rate of >1010Ks-1). This cavitation implosion is extremely confined with 1000bar pressure, and transient with 5000K temperature. This heightened energy is adequate to break groups of clusters and scatter the nanoparticles in different directions.

The effect of the ultrasonic probe (horn)

[9] At a particular frequency, the natural vibration forms a represented shape of mode with specially designed tools such as sonotrodes (ultrasonic horns) as well as boosters. The axial-mode half-wavelength sonotrode is the easiest example of the existence of predominant direction of vibrational motility together with the axis of sonotrode. Half-wavelength is explained in detail when, the variation of vibration amplitude along the length with zero point (axial) motion in the middle. The ultimate function of the horn is to amplify the frequency of the tool to the level required for efficient machining assistance, although it serves as a means of transmitting the vibrational energy from the transducer.

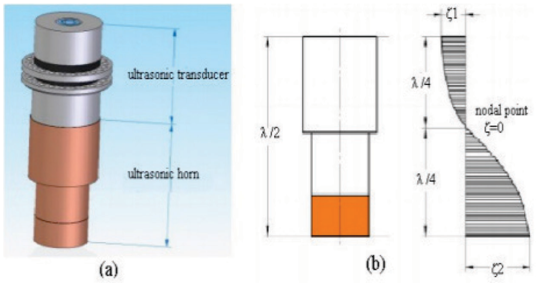

Figure 4. (a) Ultrasonic chain: (b) Stepped ultrasonic horn (correlation l - λ and amplitudes) [13]

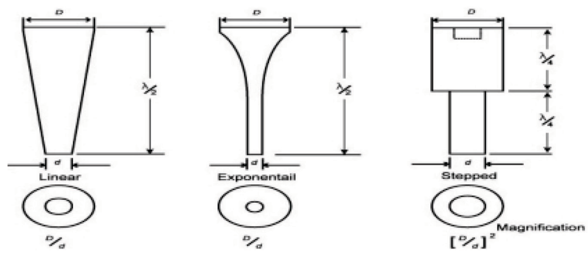

Figure 5. Horn designs

Figure 4 represents the relation between length-frequency and amplitude of the stepped horn [13]. In the ultrasonic treatment process, we insert the stepped horn in the molten metal. When it starts vibrating the horn releases acoustic waves into the molten metal. Figure5 represents few horn designs which were used in the casting industries for ultrasonic treatment.

Literature Review

Yong Yang et al [1] gave a brief outline of the research work on ultrasonic cavitation process at University of Wisconsin–Madison. They prepared Al-SiC (2%wt) MMNCs. These researchers accomplished of uniform distribution of nano-sized particles by traping the particles inside the molten liquid metal with ultrasonic cavitation process and examined the nano-sized particle distribution, as well as mechanical and microstructural properties. They concluded that the properties (mechanical) tremendously increased (more than 50%) of MMNC by comparing with same weight % of Al-SiC metal matrix composite (MMC). X. J. Wang et al [2] fabricated Mg-SiC (micro 5-20% wt) metal matrix composite by UV assisted stir casting processing. They were representing the exists an optimal time in favor of sonication and the cooperation of too long as well as too short times for the conduct, resulted in non-homogeneous particles circulation and they have proven that the ultrasonic is essential to attain uniform particle circulation and the grain size of the composite decreased along with increase of particle content, resulting in increase of yield strength, ultimate strength as well as elastic modulus. They concluded that ultrasonic treatment apparently improves the mechanical properties of composite compared with traditional stir casting.

R. Harichandran et al [3] added B4C particle reinforcement of nano and micro to the aluminium matrix. They fabricated this composite by conventional stir casting assisted by ultrasonic cavitation casting process. The author investigated mechanical properties when the B4C nanoparticles were added to the base metal. The mechanical property of the tensile test results that reveals 6% B4Cp with nanoparticles showed better properties than micro particles. This article also includes impact energy and ductility analysis of the micro and nanocomposites. In that case, micro B4Cp reinforced composites were shown to be fewer as compared to nano. The performance of the nanocomposite wear resistance notably increased with B4C particle amount and increased up to 8% (weight % reinforcement). Dinesh Kumar Koli et al[4] fabricated Al 6061- nano Al2O3 (Avg size 40 nm) composite by mechanical stirring assisted by the ultrasonic cavitation casting process. They prepared different weight % compositions (1 - 4 weight % of reinforcement with a variation of 0.5%). They investigated microstructures of nanocomposites. The microstructure analysis indicated that uniform distribution took place in Al matrix by the ultrasonic frequency at 20kHz and they conducted some mechanical tests to find out properties like hardness, tensile and compressive strength. The test resulted in a marginal increase in mechanical properties.

Jufu J, Ying et al [5] fabricated nano-sized SiC / Al-7075 matrix composite by ultrasonic dispersion technique. They examined the mechanical and microstructural properties of the prepared composite. The effect of acoustic streaming as well as cavitation of the ultrasonic experiment while mixing nano SiCp in the molten liquid. They carried out heat treatment process for the campsite and they compared the values of mechanical properties before heat treatment and after heat treatment. The heat treatment led to an improvement mechanical properties. Ravindra Singh Rana et al [6] fabricated Al-5083/ 10 weight% nano-SiC composite by mechanical stirring assisted by ultrasonic cavitation machining and they performed a wear test using Taguchi technique. The experiments were conducted at different factors and levels. The results were analyzed by ANOVA. The results showed that the highest influencing parameters are applied load along with speed and distance on the nanocomposite. A. Baradeswaran et al [7] prepared Al-Al2O3 nanocomposite by mechanical stirring assisted by ultrasonic dispersion technique. The pin-on-disc equipment was used to carry out wear analysis with controlled parameters such as distance, speed, and load. A detailed microstructural investigation of the worn surfaces was carried out with the help of SEM. A statistical analysis of wear test was successfully attained with the help of RSM technique using Minitab software. From the analysis of final results, composite AA7075-Al2O3 was evaluated for optimal controlling parameters. Yong Yang et al [10] fabricated nanocomposites (A356+SiCp) through ultrasonic-based manufacturing process. The nano-sized SiCp dispersed effectively through molten metal alloy by a high power ultrasonic process and the wettability between the particles was enhanced, which also improved the mechanical properties of the nanocomposite.

L. Nastac et al used [14] acoustic streaming and ultrasonic vibration-assisted stir casting technique for the preparation of nanocomposites (A356 alloy+Al2O3/SiCp); the nano Al2O3/SiC particles were injected into molten liquid by acoustic streaming and ultrasonic cavitation and it was found that the ductility and tensile strength of nanocomposite improved significantly after the UST treatment. OH Won-Chun el al [15] fabricated a series of grapheme oxide and graphene-TiO2 from TNB (titanium n-butoxide) through ultrasonication. The composites reported superior sonocatalytic activity and adsorptivity under ultrasonic irradiation for the chemical decomposition reaction of rhodamine B. LIU Shi-Ying et al [16] fabricated nanocomposite of Mg matrix reinforced with carbon nanotubes (CNTs/AZ91D) by high intensity ultrasonic-assisted mechanical stir casting. The microstructural and mechanical properties of the nanocomposites were examined; it was found that the percentage of elongation, tensile and yield strengths of the nanocomposite were enhanced by 42, 22 and 21 respectively. G. Cao et al [17] successfully fabricated SiCp reinforced Magnesium based nanocomposites (Mg-4Al-1Si with 2% SiCp, Mg-2Al-1Sip with 2% SiCp) through ultrasonic cavitation-assisted stir casting technique, and found that nanocomposite properties were significantly improved as compared to pure Mg alloy with retained density. Z. Porat et al [18] studied the effect of nano and micro-spheres of low melting point metallic metals and its alloys, manufactured through ultrasonic cavitation that the fast solidification of micro and nano range spheres of seven pure metals (Hg, Sn, In, Ga, Bi, Zn, Pb) due to establishment of oxides or carbides on their surfaces.

J. Babu Rao et al [19] prepared Al–fly ash nanocomposites through ultrasonic-assisted mechanical stir casting technique, investigating mechanical properties as well as properties at microstructure level. The nano-sized fly ash prepared from micro fly ash by the ball mill (30hrs). Through the results, the author concluded that the material properties (hardness, the strength of composite) increased along with content of fly ash. Xia Zhou et al [20] developed an approach for convenient fabrication of composite with reinforcement of TiN in commercially pure Al through ultrasonic cavitation. The experiment led to enhancement of wettability,and hardness due to this approach. This approach cost-effective and less complex when compared to the in-situ process; Jayakrishnan Nampoothiri el at [21] prepared nanocomposite (Al-4.4Cu/2TiB2) reaction at post-in-situ ultrasonic assisted casting process. This process involved melting of Al-4.4Cu/2TiB2 micro composite after which it was further exposed to ultrasonic treatment. Due to in-situ response ultrasonic treatment, the nanocomposites approximately enhance the mechanical properties by two times as compared to base metal. Song-li ZHANG et al [22] manufactured TiB2/Al−30Si nanocomposites with and without ultrasonic high energy field, and it was found from experimental results that the in-situ reinforced TiB2 particles are distributed uniformly and dispersed in molten liquid with high-energy ultrasonic field when compared to no higher energy ultrasonic field assisted casting. The hardness and wear resistance improved due to uniform distribution of high energy ultrasonic field. To improve corrosion resistance D.L. Duan et al [23] designed and prepared nickel epoxy/foam/SiC composites through a vacuum infusion process and found three sources that resulted in damage in the preparation of nanocomposites: the metal phase fails because of chemical, and mechanical action as well as their synergetic effect.

Conclusions

In recent years, a new technique has been developed for making MMNCs. Ultrasonic process is an advanced technique for inexpensive manufacturing of bulk MMNCs with uniform distribution of nanoparticles and superior properties. The study suggests that ultrasonic cavitation process is the most promising one to fabricate MMNCs as compared to other processes due to the following conclusions.

- Stepped prob shows the best vibrational effect compared to liner and exponential shapes.
- Compared to other materials, niobium and titanium alloys (115 mm in length and 20 mm in diameter) yield better performance due to their high temperature resistance and non reaction with molten liquid.
- 10-15 min of ultrasonic treatment leads to better distribution and dispersion of nanoparticles due to streaming transient cavitation at temperature of 5000K and atmospheric pressure of 1000 atm.
- 3/4th of the probe immersion in the molten metal shows the better sonication effect and enhanced mechanical properties.

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