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Computational analysis and experimental validation of acoustic streaming in different liquids to obtain homogeneous distribution of reinforcement particles for ultrasonic cavitation based processing

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ABSTRACT

Ultrasonic streaming and cavitation are the most predominant factors to consider for the efficient ultrasonic treatment of melts. In order to achieve a good distribution of reinforcement particles for making a metal matrix composites (MMCs), the cavitation zone and velocity of fluid must be maximum enough to disperse the particles in a homogeneous way. In normal practice, stirring takes place in a closed vessel or crucible, where efficiency cannot be seen, and simulation methods are required to inform experimental research. In this work, ultrasonic streaming in water, glycerol, and aluminium melt was numerically simulated and compared by introducing SiC particles. And the simulated results of same in water and glycerol were validated by experimental results to observe sonochemiluminescence which can lead to validate the simulated result of aluminium melt indirectly. In this work, COMSOL Multiphysics is used for the challenging coupling of pressure acoustic and particle trajectories. The simulation results show that the homogenous distribution of SiC particles is influenced by ultrasonic power, frequency, ultrasonic processing time, and immersion depth of the ultrasonic probe. These studies lay the groundwork by understanding the amalgamation of simulated results in different liquids for the application of ultrasonic treatment in metal melts. Furthermore, the presented model is numerically stable and appropriate for testing parameter variations, geometry modifications and material adjustments.

Keywords— *Ultrasonic Stirring Technique, MMC, Cavitation, Uniform Distribution of particles, probe tip diameter*

1. INTRODUCTION

Strength, and having noble tribological properties is ever growing. Industries in an automobile, aerospace, defense and other sector are in constant need for a material with good strength, toughness even at the elevated temperature which conventional material fails to provide as a combination of all the required properties. Thus, to fulfil the demand from the emerging trends, materials named "composite" were developed. Composites are a material made up from two or more constituent materials with significantly different physical or chemical properties, that when combined, produce a material with characteristics different from the individual components. Composite materials are composed of reinforcement embedded in a matrix (polymers) [1]. Metal matrix composites (MMCs) are under consideration as potential candidate materials for a variety of structural application in aerospace, transportation, defence and sports industries because the of a range of mechanical properties they possess [2].

Metal matrix composite refers to a composite system which is based on metal or alloy substrate, combined with metallic or non-metallic reinforcements. The aim of manufacturing the metal matrix composite is to combine the desirable attributes of metal and ceramics. The addition of high strength, high modulus refractory particles to a ductile metal matrix will produce a material whose mechanical properties are intermediate between the matrix alloy and the ceramic reinforcement. The matrix is usually an alloy, and the reinforcements are usually a ceramic. Metal matrix composite combines metallic properties of matrix alloys (ductility and toughness) with ceramic properties of reinforcements (high strength and high modulus), leading to greater strength in shear and compression and higher service-temperature capabilities [3].

Metal Metrix Composite is composed of a metallic matrix (aluminum, magnesium, iron, cobalt, copper) and a dispersed ceramic (oxide, carbides) or metallic (lead, tungsten, molybdenum) phase. Silicon Carbide (SiC) is composed of carbon and silicon atoms in tetrahedral arrangement with strong bonds in the crystal lattice. This produces a very hard and strong material. Introduction of SiC to the aluminum matrix substantially enhances the strength, the modulus, the abrasive wear resistance and thermal stability. SiC is easily available and has good wettability with aluminum alloys [4].

Because of the fascination powers in the middle of the particles, substantial clusters are formed. To break those clusters, blending ends up essential. Mechanical blending doesn't give the required power to break the clusters [2]. Huang et al. used COMSOL Multi physics software for the numerical simulation of acoustic waves in the melt [6]. They considered 1000W as the power of a generator. Kang et al. [7] performed numerical simulation of ultrasonic streaming and cavitation in water, liquid aluminum and liquid steel by keeping power at 200W. Jia et al. [9] used the CFD model which accounts for turbulent fluid flow, heat transfer, and the complex interaction between the molten alloy and nanoparticles. Ultrasonic generator of 1750 W and frequency of 18000 Hz was used to perform the ultrasonic treatment. The fluid flow characteristics for uniform distribution of the nanoparticles into the 6061 matrices was numerically investigated by Zhang et al. [8]. When the ultrasound is introduced, the positive and negative pressure alternate in the medium, if the pressure reaches the threshold of cavitation, ultrasonic cavitation will occur in the fluid [10]. Ayar et al. [11] simulated the ultrasonic streaming and dispersion of micro SiC particles in water and liquid aluminium. In all cases, SiC particles of average size of 44 microns were added 5% by weight of the medium. They concluded that the probe tip diameter and power can influence the uniform distribution of particles predominantly. Metal matrix composite made by stir casting are affected by various material and process parameters like stirring speed, viscosity, blade design, crucible design, clearance from bottom of the crucible to stirrer blade, pouring temperature, size of reinforcement, stirring time [1]. Clustering of particles occurs on the upper side of melt in conventional stir casting method. It was observed that few particles remain at bottom of the crucible after mechanically stirring and did not mix properly in the melt.

The objective of this work is to establish the right model formulation method for the liquid aluminium in order to achieve uniform distribution of silicon particles. As the experimental validation of ultrasonic stirring in aluminium melt is very difficult to observe, validation of water and glycerol leads to the right method of formulation which can effectively work to validate liquid aluminium's simulation work.

2. MODEL FORMULATION

In this process, an ultrasonic horn is immersed in a crucible filled with different liquids. Then horn is provided ultrasonic streaming with the help of piezoelectric transducer which runs for the pre-decided period, frequency and amplitude. The acoustic waves pass through the slurry and break the particle clusters.

The numerical simulation of the acoustic wave in water and Glycerin-water solution (added 20 % and 30% of glycerin) is carried out in COMSOL Multiphysics [13] software by using Frequency based Pressure Acoustic Module. The two-dimensional model is used for analysis. The booster of 6 mm, 13 mm and 25 mm diameter are submerged 20mm vertically into the container. The height of the liquid pool is 80 mm and a diameter of 75 mm (300ml). The ultrasound with the power of 300W and 500W having frequency 20000 Hz is introduced into the liquid pool along the gravity direction. Following cases are taken for the simulation work.

Table 1: Various cases for simulation work at 300W power

	6mm	13mm	25mm
Power-300W	Water	Water	Water
	Water +20% G	Water + 20%G	Water + 20%G
	Water + 30%G	Water + 30%G	Water + 30%G

Table 2: Various cases for simulation work at 500W power

	6mm	13mm	25mm
Power-500W	Water	Water	Water
	Water + 20%G	Water + 20%G	Water + 20%G
	Water + 30%G	Water + 30%G	Water + 30%G

Acoustic power input was transformed into a pressure source boundary as P_s.

$$P_s = \sqrt{\left(\frac{2*\rho*c*W}{\pi R^2}\right)}$$

Where W is the applied ultrasonic power and R is the end face radius of the sonotrode.

A very important parameter of the ultrasonic field one that determines to a great extent the efficiency of processing is the ultrasonic intensity I. In the simplest case of a plane wave, the intensity (W/m2) is given by,

$$\mathrm{I} = \frac{\mathrm{W}}{\mathrm{S}}$$

Where W is power, S is an area of sonotrode tip.

The sonotrode face excites predominantly travelling waves propagating through the melt. The amplitude, oscillation velocity, acceleration, and sound pressure of these waves relate to sound intensity I and frequency f by the following relations [12].

$$\mathrm{A} = \frac{1}{2\pi f}\sqrt{\frac{2I}{\rho c}}$$

$$\mathrm{V} = \sqrt{\frac{2I}{c}}$$

$$P_s = \sqrt{2I\rho c}$$

From the above equations, it can be said that as intensity changes, the amplitude, oscillation velocity, acceleration and power changes.

Table 3: Parameter and Value

Parameters	Sign	Value
Power	W	300 W, 500W
Frequency	f	20000 Hz
Density of Water	-	1000 kg/ m^3
Density of water + 20% G	-	1045 kg/ m^3
Density of water + 30% G	-	1070 kg/m^3
Diameter of probe	d	0.006m, 0.013m, 0.025m
The speed of sound in water	-	1493 m/s
Speed of sound in water + 20% G	-	1695 m/s
Speed of sound in water + 30%G	-	1695 m/s
Impedance of Glass	Z	10920000Pa. s/m^2

Analytical calculation of all cases has done using the above mathematical relations and parameters.

Table 4: Acoustic Pressure in different cases (MPa)

	Power- 300W			Power- 500W		
	6mm	**13mm**	**25mm**	**6mm**	**13mm**	**25mm**
Water	5.63	2.59	1.35	7.21	3.35	1.74
W+20% G	6.13	2.83	1.47	7.91	3.65	1.90
W+30% G	6.20	2.86	1.48	8.01	3.69	1.92

3. RESULTS AND VALIDATION

It is a fact that acoustic pressure at the tip of a horn is maximum and then due to acoustic impedance it loses its energy when it goes in a downward direction. In some cases, it has negative pressure because the motion of a piezo is consequently expansion and contraction so it may be possible that during contraction the acoustic pressure will be negative.

Analysis results give pressure distribution, the velocity of fluid flow and the trajectories of particles in mediums. The velocity and pressure obtained in fluid flow for all cases are listed in Table 5.

Table 5: Maximum velocity of flow in different cases (m/s)

	Power- 300W			Power- 500W		
	6mm	**13mm**	**25mm**	**6mm**	**13mm**	**25mm**
Water	8.26	4.04	2.63	10.69	5.22	2.63
W+20% G	10.07	6.83	3.55	13.00	11.15	4.59
W+30% G	9.93	10.83	3.47	12.82	6.53	3.47

By comparing all three cases in terms of acoustic pressure (Table 4) and velocity of flow (Table 5), optimum values are achieved in 500W power and 6mm diameter of the probe tip. So, from these results, we can conclude that liquids with a similar density and viscosity as water have the optimum values of power and probe diameter as mentioned above.

After completion of Simulation work to validate the results, Experimental work has been carried out. To perform the experiments SONICS Probe Sonicator VCX 500 was used, a horn of made up of Ti-6Al-4V was attached to the piezoelectric transducer. Further, all transparent fluids were collected in a beaker with the same volume as simulation and SIC particles were added approximately around 5-6% of total weight for each fluid. The horn was provided frequency, Energy etc. from a panel.

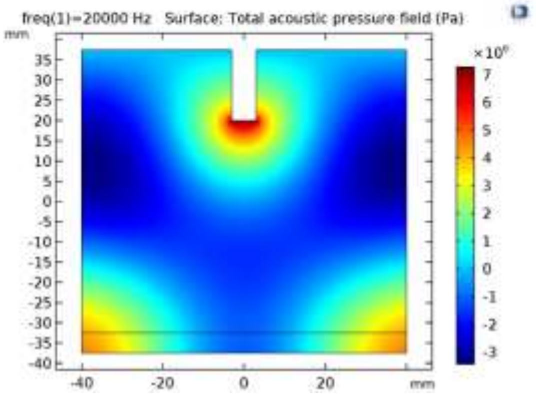

Fig. 1: Acoustic pressure in water at 500W with 6mm diameter of the probe

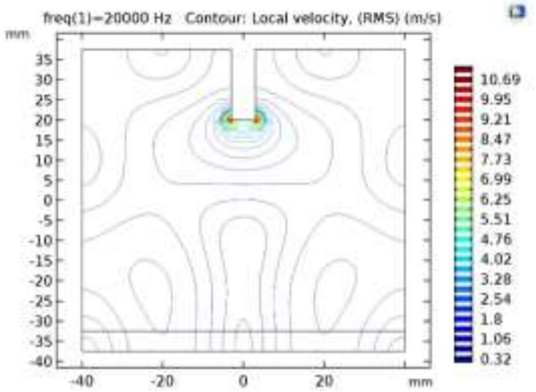

Fig. 2: Velocity contour in water at 500W with 6mm diameter of the probe

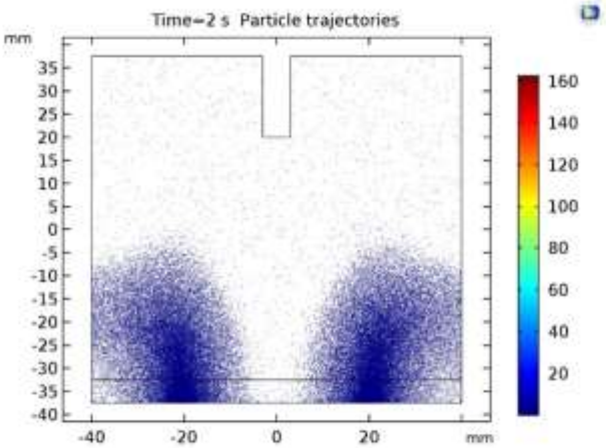

Fig. 3: Particles trajectories in water at 500W with 6mm probe

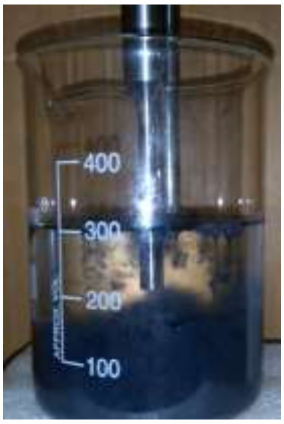

Fig. 4: Particle trajectories in water at 2 sec

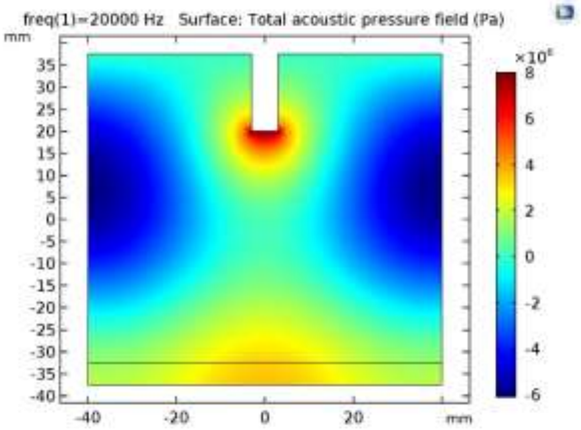

Fig. 5: Acoustic pressure in water + 30% G at 500W with 6mm diameter of the probe

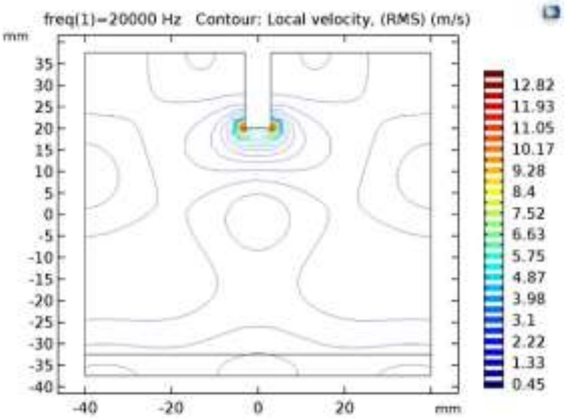

Fig. 6: Velocity Contour in water + 30% G at 500W with 6mm diameter of the probe

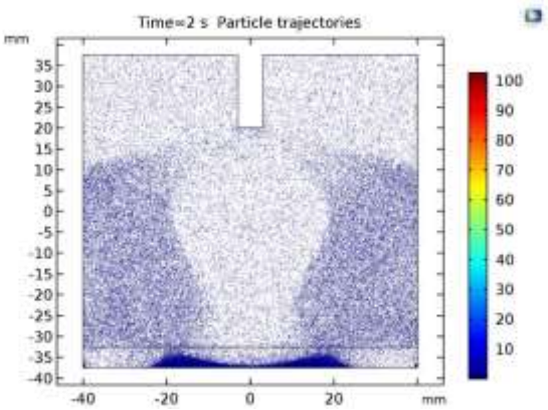

Fig. 7: Particles trajectories in water+30% G at 500W with 6mm probe

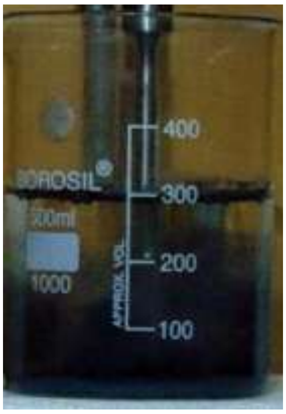

Fig. 8: Particle trajectories in water+ Glycerine at 2 sec

3.1 Ultrasonic Treatment in water and validation

Power of the Ultrasonic generator is 500W and frequency of 20000 Hz. 300 ml of water is taken for treatment. 5 grams of black SiC microparticles was added in water. Cavitation threshold pressure for water is 0.1034 MPa [5]. Following figure 1, 2, 3 and 4 show acoustic pressure distribution, velocity contours, particle trajectories and experimental validation of water.

3.2 Ultrasonic treatment in glycerine-water solution

Viscosity plays an important role in the particle movement as well as for the fluid flow. The viscosity of water is 0.001 Pa.s, and viscosity of liquid aluminium is 0.0026-0.0029 Pa.s. Glycerin is easily soluble in water at room temperature and also having high viscosity. If the Glycerin is added in water in different weight fraction gives different viscosity at a different temperature from 0-100 ˚C. Therefore, to achieve the same viscosity as liquid aluminium, 50 % by weight fraction of both Glycerin and water was added. Following fig. 5, 6, 7 and 8 show acoustic pressure distribution, velocity contours, particle trajectories and experimental validation of water + glycerin.

From image comparison we can observe satisfactory similarities between simulation and experimental outcomes, hence we can further focus on the simulation of Aluminium for the betterment of Ultrasonic stirring process and optimization of horn parameters for homogeneous particle distribution.

4. ANALYSIS OF LIQUID ALUMINUM

Simulation results of water and glycerine - water solution was carried out and validated. Accordingly, the same analysis is carried out for a liquid aluminium medium, where heat transfer in the medium is neglected. The results of simulation work for liquid aluminium are discussed in this chapter.

In the simulation, several assumptions were made:

(a) There is no energy loss due to piezoelectric effects or transmission of mechanical energy from the transducer to the horn rod.
(b) The temperature of melt kept constant (750˚C).
(c) Ignoring the ultrasonic heating effect to the fluid and the heat transfer between the container wall and the external environment.

Now, in this simulation work, following 9 cases are simulated.

Table 6: Various simulation cases for liquid aluminium

Power- 300W	6mm	13mm	25mm
Power- 500W	6mm	13mm	25mm
Power- 1500W	6mm	13mm	25mm

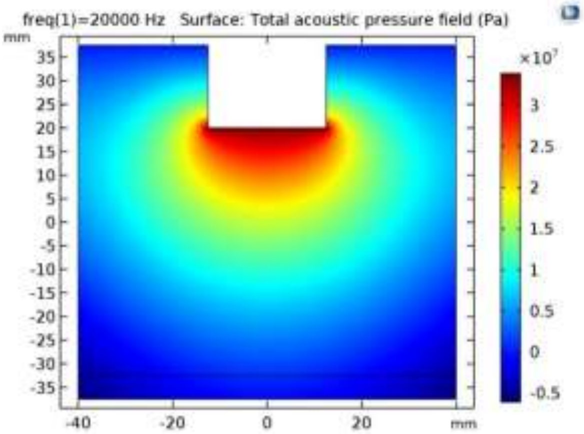

Fig. 9: Acoustic pressure at 1500W in aluminium with 25 mm diameter of the probe

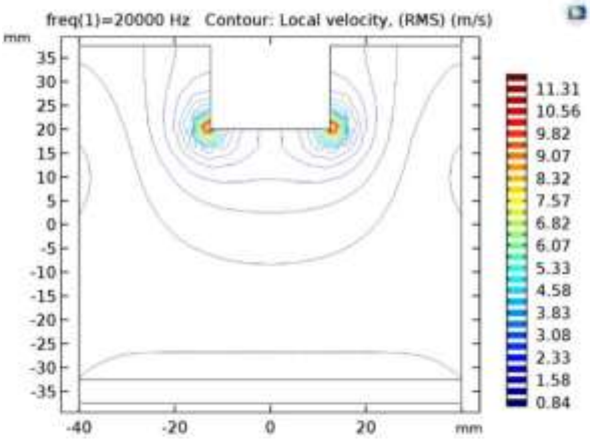

Fig. 10: Velocity Contour at 1500W in aluminium with 25 mm diameter of the probe

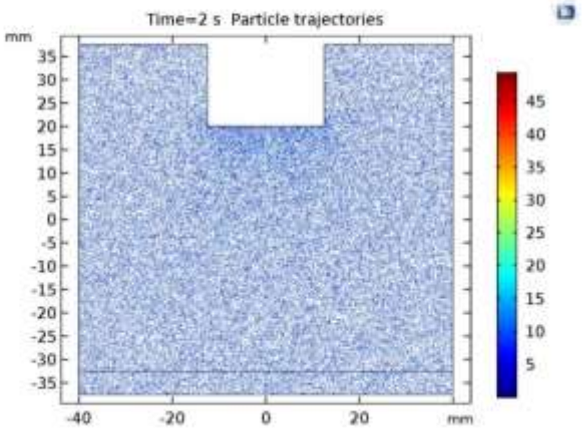

Fig. 11: Particle trajectories in aluminium at 1500W with 25mm diameter of the probe

After analyzing all 9 cases, 1500W of power and 25 mm diameter of the probe tip is optimal to obtain the uniform distribution of particles into aluminium melt for the given conditions.

5. CONCLUSION

After completion of Experimental and simulation works, the results lead to the conclusion that the simulation work for transparent mediums has very close similarities with experimental work. The simulation results of Aluminum give us an idea about how particles' dispersion takes place in MMC. The small diameter horn is effective around the only tip because of attenuation. So, the reduction rate of velocity is highest in small diameter horn while it increases as we increase the horn diameter. The Intensity of large diameter horn is sufficient enough to get uniform particle distribution. In addition, the large diameter generates high acoustic pressure which is beneficial to maximize a cavitation zone. From simulation results of various cases, the medium having a high density needs more power as well as probe diameter for effective dispersion of particles. Therefore, liquid aluminium needs at least 1500W power and 25mm diameter of the probe for complete distribution of particles for given parameters. Hence, from the particle tracing module, it is justified that large diameter horn can provide the most effective particle distribution as far as the ratio of horn diameter to crucible diameter is 1:3.

6. ACKNOWLEDGEMENT

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