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# Computational Analysis of Ultrasonic Treatment of Melt for Effective Dispersion of Reinforcement Particles

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**Abstract**

In many engineering fluids, micro or nano solid particles are introduced to enhance their effect. Introduction of nanoparticles in radiator coolant enhance its efficiency and introduction of micro/nano reinforcement particles in liquid metals enhance its mechanical properties. In most of the applications, de-agglomeration of particle clusters and uniform dispersion of particles is desirable to enhance the process. Ultrasonic streaming and cavitation can help in achieving the desirable output. In this work, the ultrasonic streaming and dispersion of micro SiC particles in water and liquid Aluminium were numerically simulated (using COMSOL multiphysics) and compared. Parameters selected for carrying out the investigations were power of ultrasonic generator and diameter (tip) of probe. Results obtained for water were validated by experimental results. The medium viscosity and density are the key factors influencing ultrasonic streaming and cavitation. The results provide reference for the ultrasonic treatment of melts for making Metal Matrix Composites (MMCs).

Keywords- Ultrasonic stirring, Cavitation, MMCs, Ultrasonic Power, Acoustic pressure, Probe tip diameter

## 1 Introduction

With the advancement of the technology, demand for materials with light weight, high strength, and having good tribological properties is ever increasing. Industries in automobile, aerospace, defense and other sector are in constant need for material with good strength, toughness even at the elevated temperature, where conventional materials fail to provide a combination of all the required properties. Thus, to fulfil the demand from the emerging trends, composite materials were developed. Particles of high strength are added in ductile metal to make metal matrix composites having

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intermediate properties. The matrix is usually an alloy, and the reinforcements are usually a ceramic. Metal matrix composite combines metallic properties of matrix alloys with ceramic properties of reinforcements, resulted in better strength [1]. Silicon Carbide (SiC) are mostly used as a reinforcement particles in aluminium matrix composites. Other widely used reinforcements are aluminium oxide ($Al_2O_3$), Boron Carbide ($B_4C$), Aluminium Nitride (AlN). Due to attenuation in the system's free energy, agglomeration occurred for making MMCs [2].

Due to the attraction forces in between the particles, large as well as small clusters are formed. To break those clusters, stirring becomes necessary. Mechanical stirring doesn't provide required power to break the smaller clusters [3]. Numerical simulations of acoustic waves in the melt had been done by Huang et al. [4] using COMSOL multiphysics software. The Power of generator was 1000 W. To analyse the acoustic pressure in the melt, two separate model was applied by them. To simulate the acoustic wave in medium, acoustic power was converted to a pressure source boundary as $P_s=P_A[\cos(\omega t)]$, where $P_A=(2\rho cW/\pi R^2)^{1/2}$, $W$ is the power of ultrasonic generator and $R$ is the tip radius of the probe. Kang et al.[5] performed numerical simulation (using Fluent), to study ultrasonic streaming and cavitation in water, liquid aluminium and liquid steel. The power of ultrasonic generator was kept 200W. Zhang et al.[6] investigated the distribution of SiC nanoparticles in liquid aluminium with the help of Ansys's Fluent DDPM (Dense Discrete phase model). The position of injecting the particles were different. In order to predict the particle trajectories, they have accounted several forces acting on a particle. They concluded that the final distribution of nanoparticles is independent of injection positions. Jia et al.[7] used 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 ultrasonic treatment. The fluid flow characteristics for uniform distribution of the nanoparticles into the 6061 matrix was numerically investigated by Zhang et al.[8]. The multiphase CFD model using the Ansys's Fluent Dense Discrete Phase Model (DDPM) and a particle engulfment and pushing (PEP) model, the dispersion of SiC nanoparticles with different injection positions, fluid flow, and locations of probe have been investigated. The frequency was set as 18000 Hz. Wang et al.[9] studied the effect of temperature range on ultrasonic treatment of primary $Al_3Ti$. They used power of the system as 4000 W and a frequency of 17500 Hz. Ultrasonic treatment of melt with high intensity was applied to an Al–0.4 wt% Ti alloy. The selected temperature ranges kept in three set : above liquidus (810 to 770°C), across liquidus (770 to 730 °C), and below liquidus (730 to 690 °C).

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 crucible to stirrer blade, pouring temperature, size of reinforcement, stirring time [1]. Clustering of particles occur 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. To overcome this issues, Researchers introduced ultrasonic vibrations in the slurries. Before conducting experiment, it is must to know which parameters play important role in Ultrasonic treatment of slurries. Such parameters are tip-diameter of probe, power of generator, frequency etc[11]. It is found that many of researchers have performed the ultrasonic treatment to liquid metals for making metal matrix composites, few of them have gone through the simulation work. The range of power and tip diameter observed in the literature are 1000W to 4000W and 20mm to 40mm, respectively with frequency of 20000 Hz.

The objective of present work is to investigate the effect of ultrasonic process parameters on cavitation region and particle trajectories in liquid medium. Initially, numerical simulation of ultrasonic treatment was carried out in the water using COMSOL multiphysics software, and subsequently experimental validation has been carried out. Later, the numerical simulation of liquid aluminium melt has been carried out at different power and probe tip diameter.

# 2 Computational Analysis

Present work includes analysis of the four cases for as listed in Table 1. Two different size of probe having 6mm and 25mm tip diameter were used. The mediums considered for numerical simulation analysis were water & liquid aluminium (melt). In all cases SiC particles of average size 44 micron were added 5 % by weight of medium.

COMSOL software was used to simulate the acoustic wave in water &liquid aluminium (melt) by using Frequency based Pressure Acoustic Module and Particle Tracing for Fluid Flow Module [12]. The probe of 6 mm and 25 mm tip diameter were submerged 20mm vertically in to the metal pool in container. The height of liquid pool was 80 mm and diameter of 75 mm (300ml of water). The ultrasound with power of 300W and 1500W having frequency 20000 Hz was introduced into the liquid pool along the gravity direction.

Table 1. Cases taken for simulation work

| Case no. | Power (W) | Tip dia (mm) | Medium |
|---|---|---|---|
| 1 | 300 | 6 | Water |
| 2 | 300 | 6 | Liquid Aluminium |
| 2 | 300 | 25 | Liquid Aluminium |
| 4 | 1500 | 25 | Liquid Aluminium |

The acoustic power was converted to a pressure source boundary as $P_s$ where $R$ is end face radius of the probe.

$$P_S = \sqrt{\frac{2*\rho*c*W}{\pi R^2}}\cos(\omega t)$$

A very important parameter of the ultrasonic field one that determines to a great extent the efficiency of processing is the ultrasonic intensity $I$. Intensity of sound is measured in Watts per square meter(W/m$^2$) is given by $I$ where $W$ is power and $S$ is area of probe tip.

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

Amplitude A is given by,

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

Table 2 shows the parameter used to analyze the ultrasonic intensity, pressure, acceleration and amplitude of the system. The speed of sound in liquid aluminium is taken as 4600 m/s [11].

Table 2. Parameters and values

| Parameter | Sign | value |
|---|---|---|
| Power | W | 300, 1500 W |
| Frequency | f | 20000 Hz |
| Density of Al. (L) | $\rho_{Al}$ | 2350 kg/m$^3$ |
| Density of Water | $\rho_w$ | 1000 kg/m$^3$ |
| Dia. of probe | d | 6, 25 mm |
| Speed of sound in Al.(L) | $c_{Al}$ | 4600 m/s |
| Speed of sound in Water | $c_w$ | 1500 m/s |
| Viscosity of Al.(L) | $\upsilon_{Al}$ | 0.0027 Pa.s |
| Impedance of Glass | $Z_{glass}$ | 10.92 MPa.s/m$^2$ |
| Impedance of Crucible (Graphite) | Z | 12.4 MPa.s/m$^2$ |

With the help of these parameters, ultrasonic intensity, acoustic pressure and the amplitude was analytically calculated which are listed in Table 3. It shows case-wise variation in ultrasound intensity, pressure and amplitude.

Table 3.Analytical values of acoustic parameter for liquid aluminium

| **Case no.** | **Ultrasonic Intensity ($W/m^2$)** | **Pressure (MPa)** | **Amplitude (µm)** |
|---|---|---|---|
| 1 | 10615711 | 5.64 | 29.9 |
| 2 | 10615711 | 15.15 | 11.158 |
| 3 | 611465 | 3.64 | 2.67 |
| 4 | 3057325 | 8.13 | 5.98 |

# 3 Results and Validation

Analysis results give pressure distribution, 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 4.

Table 4. Simulation results

| **Case no.** | **Velocity Obtained of Fluid flow (m/s)** | | **Pressure (MPa)** |
|---|---|---|---|
| | **Max** | **Min** | |
| 1 | 17.6 | 0.23 | 5.86 |
| 2 | 19.7 | 0.2 | 15.2 |
| 3 | 2.74 | 0.12 | 3.64 |
| 4 | 6.12 | 0.26 | 8.13 |

### *A. Water medium (Case 1)*

Fig 1 shows the acoustic pressure produced in water at 300W and tip diameter of 6mm. Cavitation threshold pressure for water is 0.1034 MPa [5], and cavitation is observed in more than 50% of medium. As the acoustic waves generate in the medium, it caused the suspended particles to disperse. Fig 2 shows the particle trajectories in the water medium after 1 sec. Using the similar parameters setting, physical experiment has been carried out (Fig 3). It clearly reveals close matching of particle dispersion after 1sec.

### *B. Liquid Aluminium medium (Case 2, 3 & 4)*

Fig 4 and 5 show the acoustic pressure produced in liquid aluminium using 300W and tip diameter of 6 mm and 25mm respectively. The attenuation in pressure was observed as it reaches to the bottom of the container. Based on the cavitation threshold value of 1 MPa for pure liquid aluminium [3], cavitation zone could cover most of the melt volume in case 3 (Fig 5), indicating that the tip diameter of 25 mm give better results than 6 mm for same power and medium. Fig 6, 7 and 8 show the velocity contours for case 2, 3 and 4 for fluid flow. As observed in pressure distribution, acoustic flow achieves maximum value under the tip of probe and tends to give circulation effect. It decreased significantly as reaching the bottom of the container. It is observed in Fig 6 and 7 that as the tip diameter increases (with same power), the velocity of fluid flow is significantly decreases from 19.7 m/s to 2.74 m/s. As the power increases (with same probe tip diameter), velocity of fluid flow increased from 2.74 m/s to 6.12 m/s. Fig 9 and 10 show the particle trajectories for case 3 and 4 at 1 sec. It clearly indicates that the low intensity power is not able to give proper distribution of the particles.

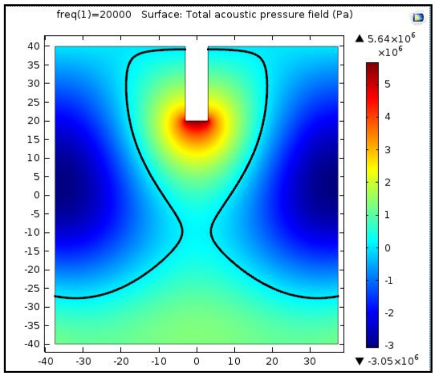

Fig 1. Acoustic pressure in water at 300 W and 6mm tip dia (Case 1)

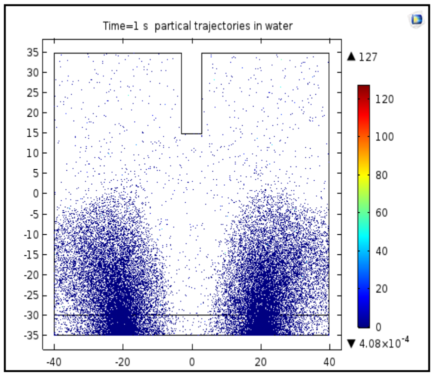

Fig 2 Simulation Result
Particle trajectories in water at 1 sec

Fig 3. Experiment result
Particle trajectories in water at 1 sec

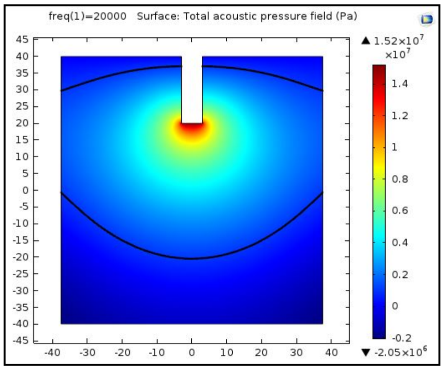

Fig 4. Acoustic pressure in liquid aluminium at 300 W and 6mm tip dia (Case 2)

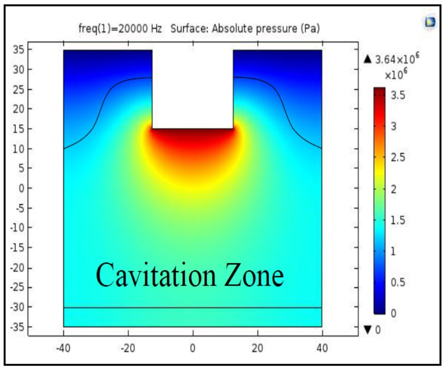

Fig 5. Acoustic pressure in liquid aluminium at 300 W and 25mm tip dia (Case 3)

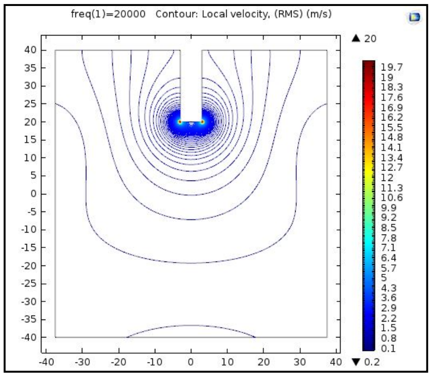

Fig 6. Velocity contour of Case 2

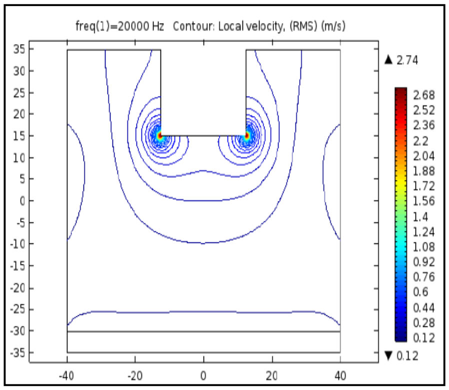

Fig 7. Velocity contour of Case 3

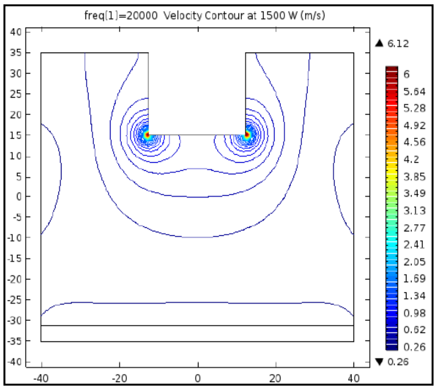

Fig 8. Velocity contour of Case 4

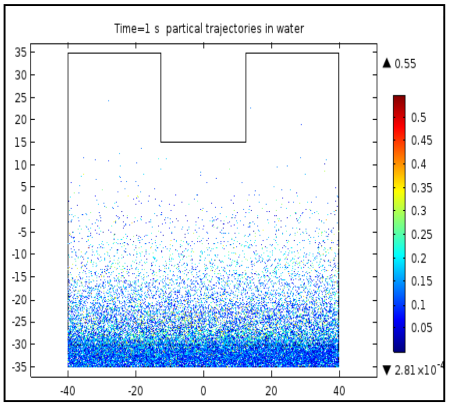

Fig 9. Particle trajectories in Case 3 at 1 sec

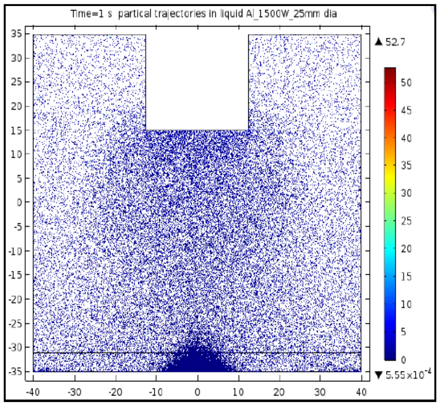

Fig 10. Particle trajectories in Case 4, (a) at 1sec.

# 4 Conclusion

Total four cases were analysed and the summary of conclusions is presented in Table 5. Numerical simulation assists in visualization of cavitation zone and the particle trajectories, leading to the better understanding of the process. As the tip diameter increased (with same power), the maximum velocity of fluid flow was decreased 86% and as the power increased (with same probe tip diameter), the maximum velocity of fluid flow was increased 220%. In case 3 (Fig 5) effective cavitation was observed in medium, but low intensity power (300W) does not create the required intensity to distribute particles in the medium (Fig 9). In liquid aluminium melt using 1500 W power and 25 mm probe tip diameter resulted in uniform distribution of particles with effective cavitation (Fig 10).

Table 5. Conclusion table

| **Case no.** | **Power (W)** | **Tip dia (mm)** | **Medium** | **RESULTS** | |
|---|---|---|---|---|---|
| | | | | **Cavitation** | **Particle Distribution** |
| 1 | 300 | 6 | Water | Yes | Yes |
| 2 | 300 | 6 | Liq. Al | No | -- |
| 3 | 300 | 25 | Liq. Al | Yes | No |
| 4 | 1500 | 25 | Liq. Al | Yes | Yes |

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