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Investigation of the factors influencing cavitation intensity during the ultrasonic treatment of molten aluminium

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ABSTRACT

The application of ultrasound to casting processes is a subject of great interest: the resulting degassing, sonocrystallization, wetting, fragmentation, de-agglomeration and dispersion yield an improved cast material with fine grain structure. However, due to the lack of understanding of certain fundamentals involved in the process, the transfer and scale-up of this promising technology to industry has been hindered by difficulties in treating large volumes of liquid metal. Experimental results of ultrasonic processing of liquid aluminium with a 5-kW magnetostrictive transducer and a 20-mm niobium sonotrode producing 17-kHz ultrasonic waves are reported in this study. A high-temperature cavitometer sensor that is placed at different locations in the liquid melt, measured cavitation activity at various acoustic power levels and in different temperature ranges. The highest cavitation intensity in the liquid bulk is achieved below the surface of the sonotrode, at the lowest temperature, and when the applied power was 3.5 kW. Understanding these ultrasonication mechanisms in liquid metals will result in a major breakthrough for the optimization of ultrasound applications in metal industries.

1. Introduction

Ultrasonic treatment of liquid metals is a powerful, environmentally friendly and cost effective process. Ultrasonic melt treatment (UST) has been practised since the 1950s; it has been shown that the application of ultrasound to liquid alloys can significantly affect the solidification process [1–3]. Ultrasonic vibrations imposed upon the liquid and solidifying metal result in the following phenomena: i) degassing leading to reduced porosity [3,4]; ii) refinement of primary phase particles and grains [3,5], iii) enhanced nucleation due to activation of substrates through wetting [3] and grain multiplication due to dendrite fragmentation [3,6], iv) reduction of segregation and agglomeration due to large acoustic pressures exerted during the collapse of cavitation bubbles [3], v) metallizing of solid/liquid interfaces through the sonocapillary effect [2,3,7], and vi) dispersing and distributing solid or immiscible phases through convection and acoustic micro-streaming [2,3]. As a result of these effects, the downstream properties of metallic alloys and their products are significantly improved [3]. Cast components with refined and uniform grain structure have many advantages including significant improvement of product quality, processability and mechanical properties. However, further research is essential to reveal the conditions of a more controllable and efficient ultrasonic processing in different alloying systems and in larger melt volumes.

The UST is primarily based on cavitation and bubble dynamics. Cavitation is the formation, growth, oscillation, collapse, and implosion of bubbles in liquids [8]. In the vicinity of collapsing bubbles, extreme temperatures (>10,000 K) [9], pressures (>400 MPa) [9,10], and cooling rates ($>10^{11}$ K/s) [11] occur. To enable the cavitation, a sufficient amount of acoustic energy should be introduced in the melt to set up a pressure variation that initiates bubbles formation. Typically a peak to peak amplitude of about 10 μm at 20 kHz corresponding to acoustic pressures of greater than 0.5 MPa is sufficient for cavitation inception in liquid Al [3,12]. As surface tension and vapour pressure at the melting point of Al are 0.871 N/m and 0.000012 Pa respectively [13], vapour bubbles are unlikely to be formed in the bulk liquid Al [14]. Thus, the majority of the cavitation bubbles in the liquid Al are considered to be pre-existing nuclei (e.g. solid inclusions with absorbed hydrogen) which develop into highly energetic cavitation bubbles due to cyclic alternating acoustic pressures of compression and tension.

Despite decades of research, the melt and solidification processing with ultrasonic vibrations is still not completely understood and properly described as most studies have been phenomenological rather than quantitative; such a quantitative study is also a requirement for the development of suitable numerical models. Specifically, in the earlier studies [1–3] cavitation onset was determined using cavitation noise monitoring devices. When the cavitation starts, emissions from the

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collapsing bubbles add to the main regular frequency component of the acoustic signal generating sub- and ultra-harmonics as well as broadband noise [2,3,15]. The beginning of the distortion of the main frequency signal can be taken as the onset of cavitation. More recently, Komarov et al. [12] took a step further and tried to measure the cavitation threshold as well as the evolution of cavitation intensity in a liquid Al melt using similar equipment to this study. In line was the study of Ishiwata et al. [16] where they attempted to evaluate the acoustic streaming velocity recalculated from the dynamic pressure exerted from the tip of the sonotrode. The pressure was measured using a mechanical scale device and was not reported. However, in both studies the different factors affecting cavitation intensity in a liquid melt were not taken into account, the cavitation intensity was reported in relative units and the pressure was not given at all, which makes them less practically useful, for example, in the validation of numerical acoustic models. In the current study, the main parameters of ultrasonic processing, such as acoustic power, melt temperature and the distance from the radiator, have been investigated using a high temperature cavitometer calibrated at the National Physical Laboratory (NPL), UK [17], which enables us to report the measured RMS (Route Mean Square) acoustic pressures in the Al melt for first time. The interpretation of the results is based on the effect of the process parameters on the measured cavitation intensity in the bulk liquid. Our aim in this work is to apply a new technique for characterising the distribution of the cavitation intensity in a melt bulk, thus revealing the optimum cavitation conditions. An in-depth understanding of how cavitation intensity and consequently the mechanism of solidification in Al are affected by such parameters is important for the optimization and up-scaling of ultrasound applications in metal industry.

2. Methodology

A charge of 5.2 kg (approximately 2 l) of commercially pure aluminium (99.7%) was introduced in a clay-graphite crucible with a diameter of 150 mm. The Al charge was then melted and heated up to 780 °C with an electrical resistance furnace. After the melting process, the liquid level in the crucible was at 110 mm. To investigate the optimum cavitation conditions for efficient UST, parameters such as the acoustic power, melt temperature and distance from the acoustic source were considered.

The ultrasonic equipment consisted of a 5-kW water-cooled magnetostrictive transducer (Reltec, Russia) with a niobium sonotrode of 20 mm in tip diameter. Ultrasonic energy was continuously introduced into the molten Al over a range of temperatures and power settings that spanned from 780 °C to 690 °C (as the alloy cooled in the furnace during experiments) and from 2.0 to 4.5 kW, respectively. Experiments were performed at a driving frequency of 17 kHz and well above the solidification temperature of liquid Al, which is 660 °C. The melt temperature was continuously monitored by a K-type thermocouple. The sonotrode was preheated and submerged to a depth of 20 mm within the melt. The intensity of cavitation was directly measured with a high-temperature calibrated cavitometer. The cavitometer used in this study is primarily designed for immersion into molten metals. It consists of a tungsten probe with a diameter of 4 mm and length of 500 mm, connected to a piezoelectric receiver mounted within a metallic enclosure (Belorussian State University of Informatics and Radioelectronics). A full account of the cavitometer can be found in [17]. Each actual measurement session was limited to 15 s to avoid heating of the piezoelectric receiver. To investigate the effect of distance relative to the sonotrode on the cavitation intensity, the measurements of acoustic emissions were taken at several points. The tip of the cavitometer probe was placed at an angle under the sonotrode and vertically at a distance of half radius (1/2 R) (about 38 mm off the sonotrode axis) and at full radius (R) (about 75 mm off the sonotrode axis) with the cavitometer probe submerged at 70 mm below the liquid free surface, as schematically shown in Fig. 1.

Signal acquisition and processing was carried out using a dedicated external digital oscilloscope device (Picoscope) that allowed real-time signal monitoring of cavitometer sensor's data and ultrasonic parameters. The raw voltage signal is transformed to the frequency domain via a Fast Fourier Transform. For each measuring point, 30 signals were acquired using a resolution bandwidth of 500 Hz; these 30 readings were averaged at each point. The time for this signal acquisition was approximately 30 × 2 ms (time gate) = 60 ms (a total of 1000 waves were analysed in each of the points of interest). There was no controlled atmosphere, and each experiment was repeated several times to ensure reproducibility of results.

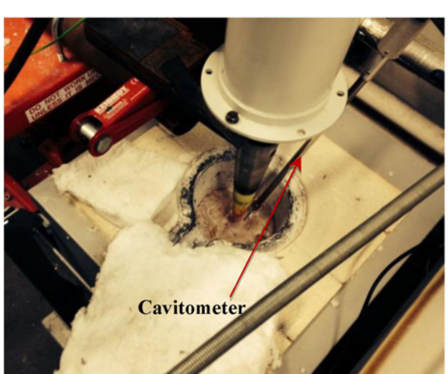
3. Experimental results and discussion

The effect of different experimental parameters on cavitation intensity is considered in this section. The cavitation intensity at a particular point is the sum of the energy intensity due to the ultrasound source, the local cavitation energy from the intensity of the cavitation bubbles, and multiple reflections from the vessel walls and free surface. However, if the acoustic pressure field is measured, only the intensity obtained at a particular frequency is converted into pressures following the methodology in [17]. At frequencies other than the forcing frequency or resonant frequency of the vessel, and their harmonics, this pressure is mainly attributed to cavitation bubble activity.

Most of the earlier experimental studies demonstrate that the cavitation intensity in the melt is the single most important parameter that determines the effects of ultrasonic processing [2,3].

3.1. Ultrasonic power

The effect of acoustic energy introduced into the liquid phase on cavitation intensity is shown in Fig. 2. Six power settings at the ultrasonic generator were used during experiments in the range of 2.0–4.5 kW,



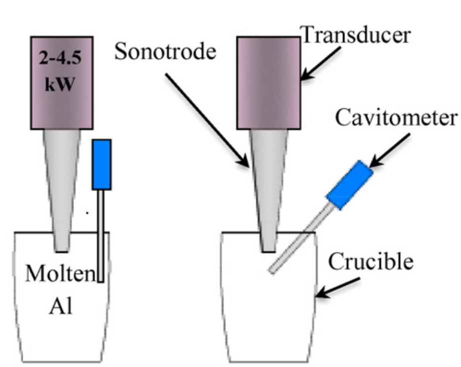


Fig. 1. A photograph and a principle diagram of the experimental test rig.

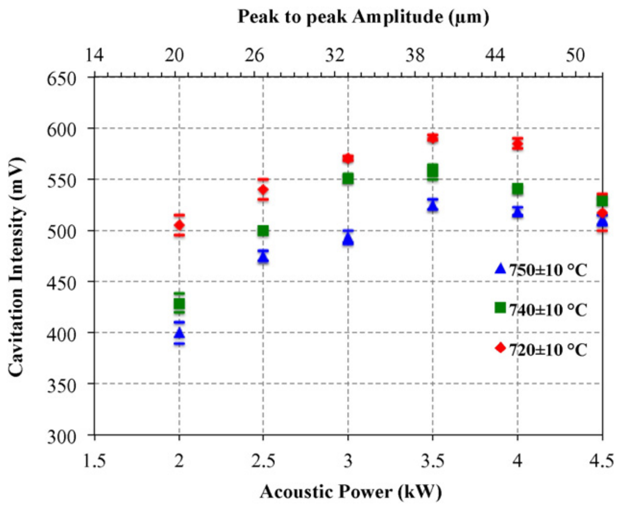


Fig. 2. Cavitation intensity measured under the sonotrode vs transducer power for three temperature ranges (17-kHz magnetostrictive transducer, Ti sonotrode with a 20 mm diameter tip, able to produce tip displacement amplitudes up to 52 μm p–p. Sonotrode was submerged 20 mm below the melt surface).

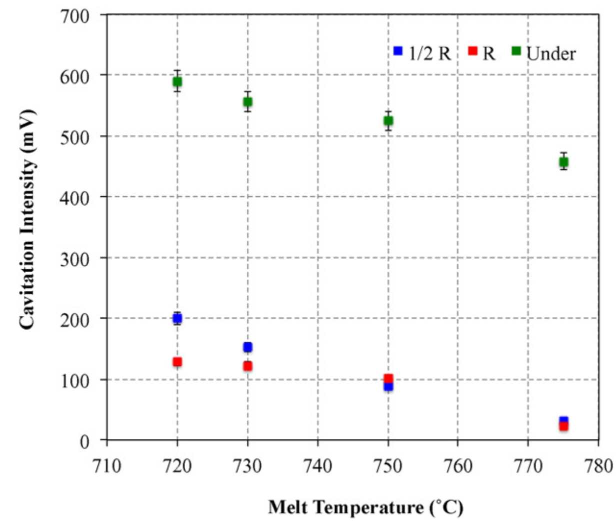


Fig. 3. Cavitation intensity measured under the sonotrode and at distance R and 1/2 R from the sonotrode. Input power was adjusted at 3.5 kW.

corresponding to peak-to-peak amplitudes inside the melt from 20 to 52 μm respectively. Three different runs were performed at three temperature ranges: i) 740–760 °C, ii) 730–750 °C, and iii) 710–730 °C. In each run, the highest temperature corresponds to 2.0 kW and the lowest at 4.5 kW. The reason is that in every run, as the furnace is opened and the cavitometer starts measuring cavitation activity, the temperature decreases. As the starting power setting was 2 kW, the melt temperature dropped by 20 °C by the time the measurement at 4.5 kW was taken.

Fig. 2 demonstrates that an increase in power input does not result in a linear equivalent increase in cavitation activity. Interestingly, the maximum cavitation intensity value is obtained at 3.5 kW (39 μm peak-to-peak) for all the cases. The reasons for this is that shielding and scattering of acoustic waves and energy due to the number of bubbly clouds, especially in the region below the sonotrode, significantly affects the propagation of the acoustic waves in the bulk liquid. Specifically for ultrasound power below 3.5 kW, the cavitation intensity increases with the acoustic power. Initially the cavitation intensity steadily increases as the number of the cavitation bubbles and bubbly clusters below the sonotrode tip is not significant, thus the propagation of the incident sound waves stays mainly unaffected. On increasing the acoustic power further, more bubbly clouds are formed but powerful acoustic streamers are able to push the bubbly clusters downwards, refreshing the liquid supply to the sonotrode tip and opening a way for the formation of new cavitation bubbles while allowing existing bubbles to migrate deeper into the bulk of the liquid. Basically, there is a trade-off situation between the sound emissions and their disruption from the cavitation bubbles, which up to the point of 3.5 kW alleviates the smooth increment of cavitation intensity with the acoustic power from the source. For intense sound fields above 3.5 kW, a large and stable cloud of bubbles is formed close to the sonication tip, consisting essentially of voids, which significantly increases sound attenuation [18]. Thus, the shielding effect reveals itself in full power and, therefore, intensity drops.

3.2. Distance from the radiator

The effect of measuring distance on cavitation intensity is shown in Fig. 3. During propagation of the ultrasound waves in the liquid melt, the intensity of the sound wave decreases with the distance from the emitter surface. This attenuation is attributable to several factors, such as reflection, refraction, or scattering of the sound, the physical properties (density, viscosity etc.) of the liquid through which the wave travels, as well as to the conversion of the kinetic energy of the wave into heat [3,18,19]. In addition, scattering of sound in the bubbly cavitation zone contributes significantly to the attenuation of the acoustic energy [18].

Three set of measurements were performed under the sonotrode (similar to Fig. 2) and at distance R and 1/2 R from the sonotrode axis. Under the same acoustic power (3.5 kW) and melt temperature, cavitation intensity significantly decreases with the increasing distance from the acoustic source. Specifically, for the same power output at 3.5 kW and similar temperature i.e. 720 °C, cavitation intensity rapidly drops about three-fold as the distance increases from 0 to 1/2R. On further increase of the distance, the decrease is about 40%. However, when temperature was significantly higher i.e. >750 °C, the cavitation intensity did not vary much between 1/2R and R. This could be related to very little attenuation of the sound wave that escaped the cavitation zone (and lost its power) and travels through the liquid metal. These results clearly demonstrate the confinement of active cavitation processing zone in liquid aluminium. Results are also in a good agreement with the work of Ishiwata et al. [16] where they showed that the dynamic pressure expressed in terms of streaming velocity significantly attenuated with the distance from the sonotrode.

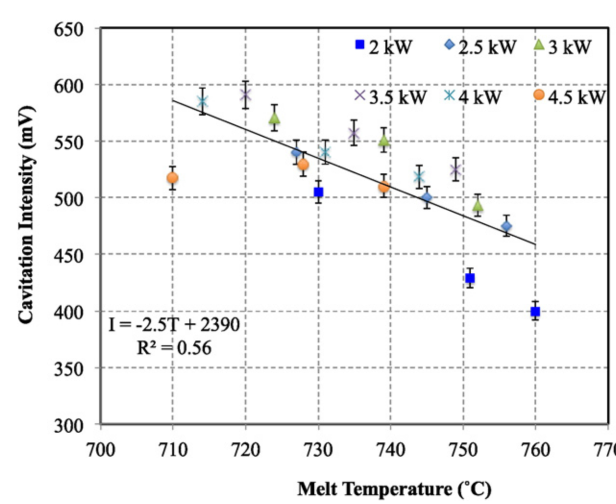


Fig. 4. Cavitation intensity as a function of the melt temperature for six different power settings. Measurements were taken below the sonotrode.

3.3. Melt temperature

In Fig. 4, results from Fig. 2 are re-plotted against temperature drop. The effect of temperature drop on cavitation intensity is shown for a series of measurements performed below the sonotrode. Experiments were conducted to determine the optimum temperature where cavitation intensity reaches the highest values. Quantitative analysis of the effect of melt temperature and acoustic power showed that cavitation intensity constantly increases with decreasing temperature, showing a linear trend which can be expressed with the following relationship (Eq. 1):

$$I = -2.5\,T + 2390 \quad (1)$$

where I is the ultrasonic intensity (mV) and T is the melt temperature (°C). It should be noted that, at the highest power setting, ultrasound is so powerful that a relatively high and similar level of cavitation activity is maintained throughout the different temperature regimes.

As temperature drops, it is easier for cavitation bubbles to form due to the decreasing with temperature solubility of hydrogen in liquid Al [3]. Consequently, more new nuclei are formed, generating numerous cavitation bubbles and increasing cavitation intensity at the same input acoustic power. On the other hand, as melt temperature decreases, the melt becomes more viscous and dense; so the formation of cavitation bubbles is more difficult, yet these bubbles produce more pressure when they collapse [20]. Moreover, the cavitation zone in the viscous and dense environment should be less extended in volume and therefore provide less shielding. Hence, these competitive aspects would determine the final cavitation intensity in the bulk liquid at lower temperatures. Results are also in a good agreement with the studies presented in [3] where the effect of temperature on the cavitation threshold is shown for Al-6% Mg melt. With the temperature drop the cavitation threshold increases implying a more aggressive cavitation regime and thus higher cavitation intensity levels.

The measured intensities can be re-calculated to acoustic pressure using calibration and procedure described elsewhere [17]. The intensity of the measured acoustic signal at the driving frequency (17.5 kHz) was converted to acoustic pressure. Two sets of measurements were performed from that, at 720 °C (similar to Fig. 2) and closer to the liquidus, at 690 °C. Apart from the temperature, the input power was varied as well. The plots in Fig. 5 show the change of the RMS acoustic pressure with the nominal applied power for two temperatures 720 and at 690 °C. To the best of our knowledge, this is the first time where the acoustic pressure measurements were conducted in liquid Al with varying power and temperature.

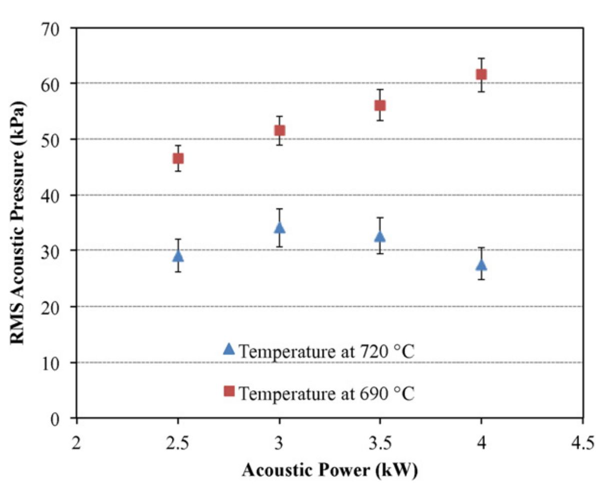


Fig. 5. Variation in RMS acoustic pressure of the driving frequency at two different melt temperatures for various power settings.

It can be clearly seen that at the lower temperature, the acoustic pressure is significantly higher with an upward linear progression with the increasing input acoustic power. In contrast, at the higher temperature the acoustic pressure changes relatively weakly, within 10–15%.

The measured acoustic pressure consists of several components, i.e. the acoustic pressure from the sound wave of the driving frequency and its reflections and from pressure surges upon collapse and pulsation of cavitation bubble. The results presented in Fig. 5 take into account only the pressure related to the driving frequency at 17 kHz. This acoustic field is greatly attenuated by the cavitation zone and, therefore, will be a function of the size of this zone and the amount of cavitation events in it (cavitation index [18]). The measurements are performed under the sonotrode and correspond either to the lower part of the cavitation zone or the bulk volume immediately below the cavitation zone. With taking this into account, the lower measured pressure at 720 °C can be interpreted as a result of stronger acoustic shielding by the cavitation zone containing more bubbles and also to a greater volume occupied by the cavitation zone due to the lower viscosity and density of the melt. At 690 °C, due to the lower hydrogen solubility the formation of bubbles maybe facilitated (cavitation threshold is lower) but at the same time less bubbles are formed due to the viscous environment, requiring more acoustic energy for further cavitation development. Also, the cavitation zone can be smaller with correspondingly lesser shielding. The measured pressure is lower than expected for cavitation conditions. However, in the absence of the shielding we can estimate that actual acoustic pressures generated at the tip of the sonotrode or in the bulk will be more than 10 times larger [18]. The calculated pressure values for liquid Al were reported to be in the range of 0.5 MPa before the cavitation onset [3], which corresponds well with the values measured in our work, providing a multiplication factor of 10.

These relationships between temperature, power and distance are very important for industry as a more controllable process of the ultrasonic treatment of alloy melts can be established by adjusting the melt temperature and the amplitude of vibrations (input power). Advantages, in most of the cases, are related with the generation of the maximum cavitation intensity utilizing the input energy efficiently. Consequently, apart from the structural improvements on the final products this in turns can potentially have an impact in environmental savings with further economic benefits.

3.4. Contribution of the experimental parameters

Having discussed the conditions affecting the cavitation intensity in an Al melt under ultrasonic vibrations, a comparison of the tested parameters was conducted to estimate their impact on the cavitation intensity. This was achieved by comparing the measured cavitation intensities at extreme values of the variable parameters. Correlations among the initial with the final values of the cavitation intensity as measured during the change of acoustic power, distance from the source and melt temperature drop were obtained. Specifically, according to Figs. 2 through 4 the minimum and maximum cavitation intensity was achieved at i) 2 and 3.5 kW power input, ii) at distance R from the sonotrode axis and below the sonotrode, and iii) during temperature drop between 750 and 720 °C (for a comparable input power of 3.5 kW), respectively. The percentage influence of each of the studied parameters to the cavitation intensity was calculated using the following expression (Eq. 2):

$$I_{int} = \frac{I_i - I_0}{I_i} \cdot 100\ [\%] \quad (2)$$

where I_{int} is the mean percentage of increment (percentage change) of the cavitation intensity between different stages I_i and I_0 corresponding to different parameters.

Table 1
Percentage of influence of the distance from the sonotrode, vibration amplitude (power input) and of the melt temperature on the cavitation intensity levels in liquid Al.

Variable	Experimental conditions	Percentage of influence (%)
Acoustic power from 2 to 3.5 (kW)	Temperature: 750 °C Distance: below the sonotrode	12%
Effective distance from the source to distance R (mm)	Power: 3.5 kW Temperature: 750 °C	74%
Melt temperature from 750 to 720 (°C)	Power: 3.5 kW Distance: below the sonotrode	14%

Table 1 shows the percentage of influence the vibration amplitude, the distance from the source, and the melt temperature have on the measured cavitation intensity in liquid Al; the higher the percentage, the greater the impact on the cavitation intensity.

Specifically, when distance was considered, two different measurements were performed: below the sonotrode where the maximum intensity was monitored and at the edge of the crucible (near the side wall) where the cavitation intensity is the lowest. Temperature was kept at 750 °C and power input was at 3.5 kW where the maximum cavitation intensity was monitored. Equally, when the effect of amplitude (input power) was examined, two different measurements were taken at 3.5 kW where the maximum cavitation intensity was measured and at 2.0 kW with the lowest cavitation intensity levels. Temperature was kept again at 750 °C with measurements taken only below the sonotrode where the highest cavitation levels were monitored. Finally, when the effect of temperature was examined, two different temperature regimes were considered at 750 and at 720 °C while power input was at 3.5 kW with the measurements taken below the sonotrode.

We can conclude that the cavitation intensity is mainly influenced by the distance from the source (74%) rather than the melt temperature or the input power to the melt, both having similar influence percentages of 14% and 12% respectively.

4. Conclusions

The measurements of cavitation intensity and acoustic pressure were performed in liquid aluminium using a calibrated high-temperature cavitometer. Several practically important processing parameters were varied and their significance for the ultrasonic melt processing was quantified for the first time. Key findings of the study are:

i) Quantitative analysis of the effect of ultrasonic amplitude showed that there is an optimum power setting (at 3.5 kW/ 39 μm p–p) where bubbly structures and vibration amplitude reach a physical balance and cavitation intensity acquires maximum values.
ii) Cavitation intensity measurements have shown that shielding of the acoustic wave is more pronounced at higher acoustic powers implying that a large amount of the supplied energy is consumed within the cavitation zone and not propagated into the bulk; hence the efficiency of cavitation treatment of the melt alloy depends weakly on the increasing acoustic power.
iii) When temperature drops, larger acoustic pressure fields in the cavitation zone and a more intense cavitation regime are generated, which is beneficial for efficient melt treatment.
iv) Distance plays a predominant role in the attenuation of acoustic intensity in liquid aluminium alloy, thus the melt treatment is more efficient closer to the power source.
v) Acoustic pressure measurements with regards to the melt temperature were conducted in liquid aluminium for the first time. At temperatures closer to the liquidus temperature, acoustic pressure linearly increases with the power increment implying the lesser effect of acoustic shielding.

The findings of this study along with the used technique are needed for eventual industrial implementation and scale up of ultrasonic processing technologies. A better control of the acoustic pressure fields and cavitation development holds the key for the optimization of solidification processes.

Acknowledgments

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