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Comparison of cavitation intensity in water and in molten aluminium using a high-temperature cavitometer

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Abstract. The application of ultrasound to industrial casting processes has attracted research interest during the last 50 years. However, the transfer and scale-up of this advanced and promising technology to the industry have been hindered by difficulties in treating large volumes of liquid metal due to the lack of understanding of certain fundamentals. In the current study, experimental results on ultrasonic processing in deionised water and in liquid aluminium (Al) are reported. Cavitation activity was determined in both liquid environments using an advanced high-temperature cavitometer sensor. In water, the highest cavitation activity is obtained for the lowest sonotrode tip amplitudes. Below the sonotrode, the cavitation intensity in liquid aluminium is found to be four times higher than in water.

1. Introduction

In recent years, there has been an increased interest in fundamental and applied investigations on metal solidification with the use of ultrasound [1]. Ultrasonic treatment of metallic alloys is driven by cavitation and bubble dynamics and it has been proven to be effective and promising for degassing and refining grain structure [2, 3]. However, its industrial application remains rather limited. Commercial-scale ultrasonic melt treatment is hindered by the lack of fundamental knowledge and practical models needed to optimize the ultrasonic treatment conditions, particularly those concerning, (i) the interaction between ultrasound-induced cavitation and the processed volume (ii) the characteristics of cavitation zone in molten metals, which currently limits this advanced processing to laboratory scale. The development of such knowledge is required for any major technological breakthrough.

In the current study, two different approaches were used. The first one is related to the characterisation of cavitation activity within a particular water vessel; while the second one investigates cavitation activity within molten Al. Ultrasonic excitation for both cases is achieved by utilising an ultrasonic transducer with a sonotrode submerged into the melt. Measurements at various locations across the vessels revealed noticeable spatial variations in the cavitation activity. The local cavitation phenomena were explained based on the spectral characteristics of acoustic emission.

2. Methodology

In this study, two different experimental setups for water and Al were used, as shown in Figure 1. In the case where water was treated by sonication, a titanium sonotrode with a 40-mm tip diameter was driven by a 1-kW piezoelectric transducer which oscillates at a frequency of 20 kHz producing maximum peak-to-peak amplitude of 34 μm (Hielscher/Germany) at the tip. The tip of the sonotrode was submerged 20 mm below the water surface. A 3 litre cylindrical vessel with diameter of 16 cm and height of 15 cm filled with 2 litres of deionised water was used. The reason for choosing this geometry is that the geometrical features of this water vessel are very close to the crucible's geometry (dimension 15 cm/height 21 cm) where Al melt is treated. Water temperature was maintained at 22±1 °C. Experiments were performed at various distances across the central axis of the vessel, with the sonotrode placed at two different positions i) in the centre of the vessel and ii) near to the vessel's wall in order to investigate the effect of positioning on the cavitation intensity. All experiments were carried out with sonication amplitude adjusted at 50% (p-p 17 μm) and 100% (p-p 34 μm).

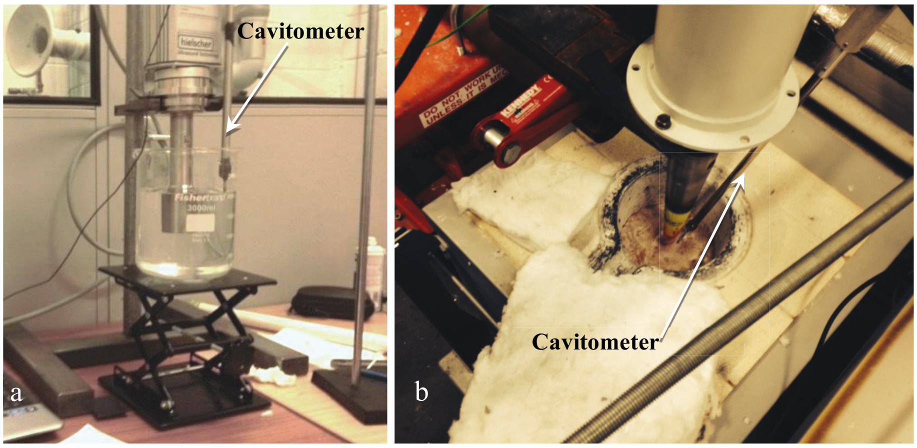

Figure 1: Experimental test rigs for a) Water b) Molten Al.

Pure Al was selected because it has been extensively studied and widely used in metallurgical, automotive and aerospace industry as an alloy base. Additionally, liquid Al and water have very close kinematic viscosities while their Newtonian behaviour is similar [4] making water a frequently used physical model of liquid Al. The charge of 5.2 kg (equal to 2 litres) of Al was melted in a clay–graphite crucible coated with boron nitride (BN) from inside at a temperature of 760 °C. The ultrasonic equipment consisted of a 5 kW magnetostrictive transducer (Reltec, Russia) with a Ti sonotrode of 20 mm in diameter submerged to a depth of 5 mm in the melt. Experiments were performed at a driving frequency of 17.5 kHz only for the case of 3.5 kW (p-p amplitude 39 μm inside Al melt). The tip was preheated and the melt temperature was controlled during the process. There was no controlled atmosphere.

The intensity of cavitation was directly measured using a calibrated high-temperature cavitometer (Belorussian State University of Informatics and Radioelectronics) (Figure 1). Cavitometer consists of a tungsten probe with a diameter of 4 mm and a length of 500 mm connected to a piezoelectric receiver mounted within a metallic enclosure. A full description of cavitometer can be found in [5]. The signal acquisition and processing was carried out using a dedicated external digital oscilloscope device "Picoscope" (Pico Technology/UK) that allowed real-time signal monitoring of the cavitometer sensor's data and ultrasonic parameters.

3. Experimental results and discussion

Figure 2 shows a typical acoustic spectrum for water and liquid Al as received by the cavitometer. The acoustic sources in water and in Al working at 20 kHz and 17.5 kHz, respectively, produce broadband signals well into the high frequency domain associated with the activity from cavitation bubbles. The general shape of the spectrum plot is similar, thus reinforcing further the opinion that water and Al can share similar behaviour under ultrasonic treatment. Specifically, the prominent fundamental frequency component (f_0) is clearly shown in both graphs with further contributions from sub- and ultra-harmonic frequencies. The difference is that harmonics in molten Al are less prominent, implying that cavitation activity has not been fully developed yet or that the acoustic signals received by the cavitometer in liquid Al are much lower than expected due to the attenuation effects from the liquid.

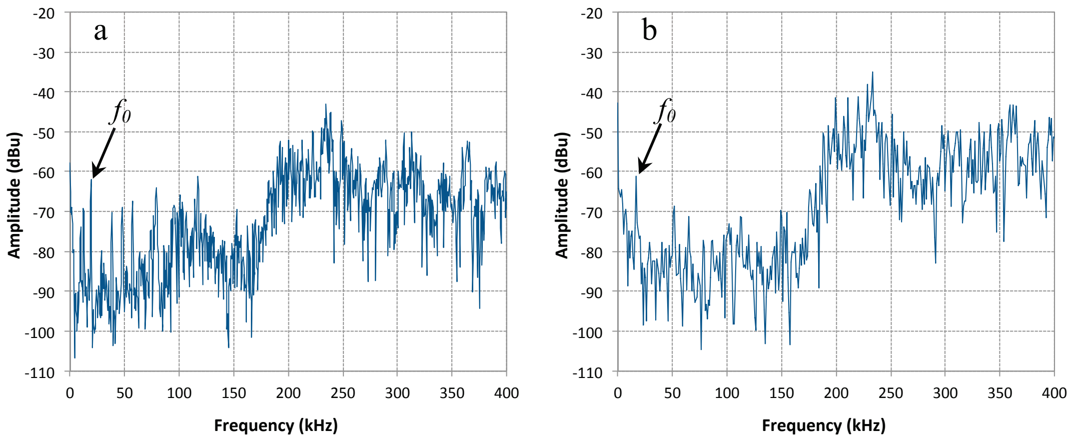

Figure 2: Acoustic spectrum generated by ultrasonic transducer a) 20-kHz piezoelectric in water and b) 17.5-kHz magnetostrictive in Al. Measurements were taken below the sonotrode's surface

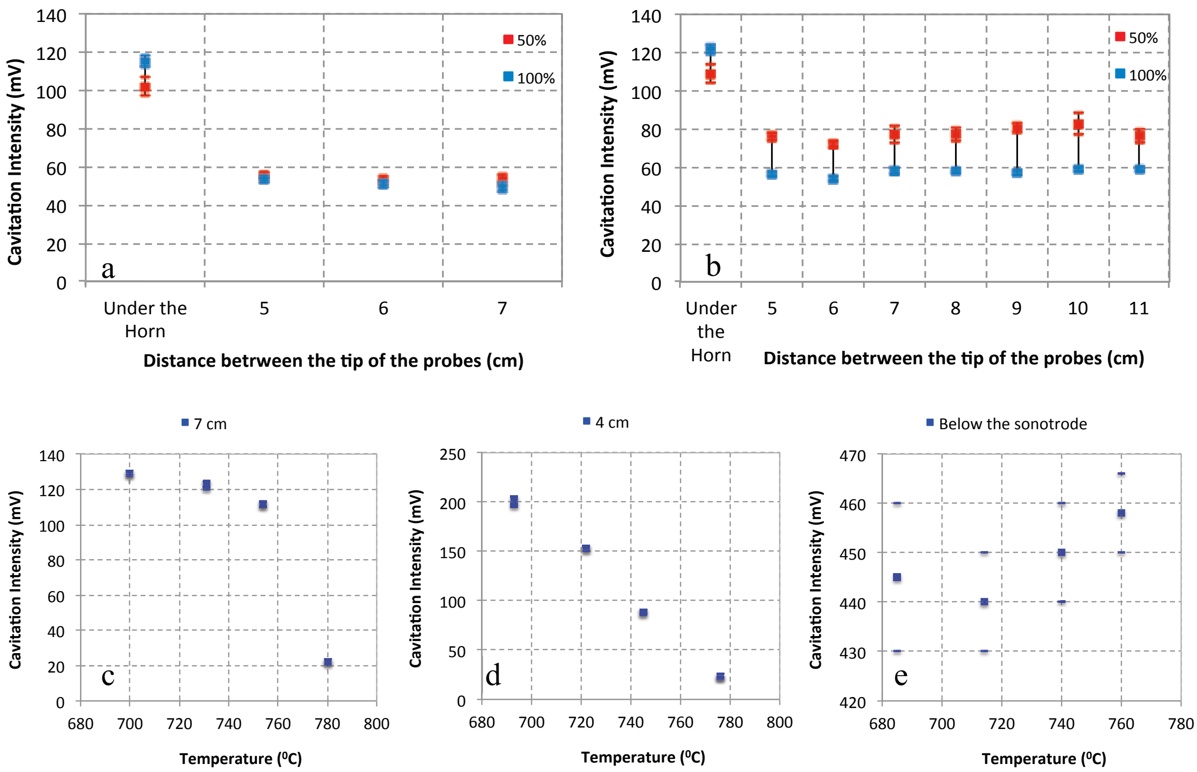

Figure 3: Cavitation activity measured in: a-b) water for two positions of the sonotrode a) near to the side wall b) in the centre of the cylindrical vessel, as a function of distance between the centre tip of the cavitometer and the sonotrode under mechanical amplitudes of 50% and 100% and c-e) liquid Al with respect to temperature drop at various distances from centre tip of sonotrode with the sonotrode placed in the centre of the crucible.

One should take into account that molten Al does not contain as many nuclei or pre-existed bubbles as in water, making the inception and development of powerful cavitation more difficult [1]. Although, the overall broadband component (>200 kHz), which is generated by the collapsing bubbles of a wide range of sizes with their shock emissions and liquid jets contributing further, is slightly higher in liquid Al than that of the water implying a more prominent activity from cavitation bubbles. Specifically, at higher frequencies i.e. in the range of 200–250 kHz, prominent peaks are shown, suggesting nonlinear activity from numerous cavitation bubbles. This leads us to a preliminary conclusion that in the studied melt the activity of bubbles with resonant sizes of 10–15 μm (according to Minnaert's equation [6]) could possibly prevail in the cavitation regime. This is in agreement with our recent in-situ study of cavitation in Al melts, showing that the majority of cavitation bubbles are indeed in that particular range [7]. Note that the hump at 160 kHz is attributable to the variation in the sensitivity response of the cavitometer.

Figure 3 shows the spatial variation data of the cavitation activity for different positions of the sonotrode and the cavitometer probe within the water vessel and the crucible. It can be clearly seen in Figures 3a, b that less power is more effective in producing higher cavitation activity in water. In the case when the sonotrode was placed in the centre of the cylindrical vessel, 50% power was producing slightly higher cavitation activity levels than 100%. However, when the sonotrode was moved near the side wall, the 50% output produces about 30% more cavitation activity compared with 100%. These amplitude differences regarding the power output and the positioning of the sonotrode are attributable to two factors; a) to the shielding and scattering effects; where the higher output level, i.e. 100%, produces an intense region of cavitation very close to the sonotrode tip surface, which prevents the further propagation of ultrasound into the liquid, thus attenuating the signal received by the cavitometer sensor and b) to the fact that activity can be higher near to the wall as bubbles can collapse easier due to the solid interface and also cavitation nuclei or many microscopic air bubbles are more available due to the surface roughness of the glass wall. Results are in a good agreement with the works of Rozenberg [8] and Hodnett et al. [9]. Additionally, when the cavitometer was placed below the sonotrode, intensity was measured to be similar to that at 100%.

Another interesting feature is that cavitation activity significantly increases with temperature drop in liquid Al as shown in Figures 3c-3e. This clearly appears in the areas away from the main cavitation zone. Below the sonotrode, the intense region of cavitation maintains high levels of cavitation activity regardless of temperature variation. The measurements of raw acoustic signal in liquid Al indicate that acoustic cavitation is much higher than in water e.g. 4 times higher in locations below the sonotrode. Thus, cavitation activity is expected to be much higher in liquid melts.

4. Conclusions

1) Ultrasonic processing of molten Al produces an acoustic spectrum comparable to water. The analysis of the broadband spectra showed that cavitation intensity is higher in liquid Al than in water implying a more prominent activity from cavitation bubbles.
2) Lower power outputs i.e. 50%, seem to be the best setting for producing the higher cavitation activity throughout the treated volume, suggesting nonlinearity in energy transfer to the liquid, while the location of the sonotrode is seen to affect cavitation activity within the liquid.
3) Cavitation intensity significantly increases with temperature drop in liquid aluminium, except for the region below the sonotrode where intense cavitation is maintained regardless of temperature variations.

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