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In situ observation and analysis of ultrasonic capillary effect in molten aluminium

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ABSTRACT

An in situ synchrotron radiographic study of a molten Al–10 wt% Cu alloy under the influence of an external ultrasonic field was carried out using the Diamond-Manchester Branchline pink X-ray imaging at the Diamond Light Source in UK. A bespoke test rig was used, consisting of an acoustic transducer with a titanium sonotrode coupled with a PID-controlled resistance furnace. An ultrasonic frequency of 30 kHz, with a peak to peak amplitude at 140 microns, was used, producing a pressure output of 16.9 MPa at the radiation surface of the 1-mm diameter sonotrode.

This allowed quantification of not only the cavitation bubble formation and collapse, but there was also evidence of the previously hypothesised ultrasonic capillary effect (UCE), providing the first direct observations of this phenomenon in a molten metallic alloy. This was achieved by quantifying the re-filling of a pre-existing groove in the shape of a tube (which acted as a micro-capillary channel) formed by the oxide envelope of the liquid sample. Analytical solutions of the flow suggest that the filling process, which took place in very small timescales, was related to micro-jetting from the collapsing cavitation bubbles. In addition, a secondary mechanism of liquid penetration through the groove, which is related with the density distribution of the oxides inside the groove, and practically to the filtration of aluminium melt from oxides, was revealed. The observation of the almost instantaneous re-filling of a micro-capillary channel with the metallic melt supports the hypothesised sono-capillary effect in technologically important liquids other than water, like metallic alloys with substantially higher surface tension and density.
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1. Introduction

When a liquid volume is subjected to a high-intensity ultrasonic field close to the entry of narrow spaces such as capillaries, canals, pores and voids an abnormally high rise of the liquid is observed inside these narrow channels. This phenomenon is known as the sono-capillary or ultrasonic capillary effect (UCE) and the research was first initiated in the former Soviet Union in early 60's and 70's [1,2]. More recently, UCE attracted the attention of researchers with regard to liquid filtration and impregnation [3]. Several hypotheses regarding the driving mechanism of the UCE have been developed [4–10]. At the same time, a robust theory explaining the driving mechanism of the UCE has not been found yet as there are only few real time observations of UCE available that can provide us with a coherent validation of the existing theories.

Specifically, experimental studies on water showed that the extreme dynamics of the acoustic cavitation bubbles were observed at the entry to capillary tubes, suggesting that cavitation generation is a requirement of the sono-capillary phenomenon assisting the penetration of the surrounding liquid into capillary micro-channels [5]. Dezhkunov et al. [6] showed that in the absence of cavitation no rise of the liquid in a capillary was recorded. As the amplitude of vibrations increased and a cavitation cloud appeared at the capillary channel inlet, the liquid raised inside the capillary, implying that the cavitation activity played a crucial role in the UCE. Additionally, Sankin et al. [7] suggested that the sono-capillary effect might be explained, at least partially, by a counter pressure arising from the bubbly cloud and the capillary interaction. Although they stated that the point of application of the counteracting force influencing the liquid flow in the capillary had yet to be found. In line with these research findings was the recent work of Tamura et al. [8], who suggested that the cavitation bubbles formed at the open end of a capillary tube contribute to

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the pressure accumulation within the tube leading to the raised height of the liquid. In contrast, Rozina et al. [9], proposed that the specific cavitation phenomena (the shock waves and high velocity cumulative jets) were not the decisive factor for the formation of liquid flow penetrating micro-capillary channels and also reported that the process of the filling of dead-end capillaries with a liquid in the ultrasonic field, was affected mainly by the dissolution of gas inside the capillary rather than cavitation [10]. The role of cavitation and cavitation bubble dynamics in the UCE phenomenon therefore remains an open subject for further investigation.

Despite the continuing debate on the mechanisms of the sono-capillary effect, the application of UCE is extremely important for industry as it underlies intensification of many important technological and chemical processes connected with oil production [11], bio-sludge and biomass processing [12], membrane filtration [13], ceramic filters [14], micro-biology [15] as well as advances in metal casting industry and the production of high quality castings [16]. The effects induced by ultrasound in liquid media and their influence on the industrial metal processing have been studied for many years under the umbrella of acoustic cavitation [16,17]. Although these effects are widely used, there is a large room for technology improvement that requires better understanding of the involved mechanisms. In addition to filtration, wetting and impregnation applications, the forced filling of small-scale defects formed during solidification, e.g. grooves, voids, crevices, which could eventually lead to crack formation and propagation, can potentially reinforce the as-cast structure and improve structural integrity of the as-cast metal.

The experimental studies of UCE in liquid metals have been hindered until recently by obvious limitations such as high temperatures, opaqueness and chemical activity of the melts. Nowadays X-ray imaging technology, available through the third generation synchrotron radiation sources, is extensively applied in the in situ and real-time investigations of liquid metals and their solidification processes [18–20].

In the current study, the direct observation of the penetration of a liquid metal into a pre-existing groove (acted as a micro-capillary channel) during the ultrasonic processing of a liquid Al–10 wt% Cu alloy, enabled by the Diamond Light Source – the national synchrotron facility of the UK, is used for testing some of the theoretical approaches behind the UCE. To the best of our knowledge this is the first time when the filling of a capillary with the liquid metal under cavitation conditions has been observed. Our results showed that a possible mechanism responsible for the UCE is the collapsing activity of cavitation bubbles in the vicinity of the micro-capillary inlet. The results are in a good agreement with the hypothesis regarding the cavitation nature of the UCE as reported by Dezkunov and Leighton [5,21–23] who analysed this phenomenon in water. Through this novel research we are now able to help answer the long-stated questions: (a) can ultrasound assist the penetration of capillary channels in the molten metals, (b) what are the governing mechanisms and (c) are these mechanisms related with the local activity of the cavitation bubbles? The discovery of the almost instantaneous re-filling of a micro-capillary channel with the metallic melt is highly important, as it appears to confirm the existence of the sono-capillary effect in technologically important liquids, other than water, like metallic alloys with substantially higher surface tension and density.

2. Methodology

In situ synchrotron X-ray radiography studies of a molten Al–10 wt% Cu alloy subjected to ultrasonic processing were carried out using the Diamond-Manchester Branchline at the Diamond Light Source (National Synchrotron Facility in UK). A bespoke ultrasonic test rig, consisting of an ultrasonic processor coupled with a Ti sonotrode and a PID-controlled resistance furnace (see [24]) was used (Fig. 1a). A split furnace with a small X-ray translucent window to allow the X-rays to pass with minimal attenuation was vertically aligned with the direction of the X-rays as shown in Fig. 1b. A specially developed crucible made of BN (boron nitride) was placed in the centre of the furnace and in line with the window. The BN crucible (key dimensions shown in Fig. 1b) was used due to its low X-ray attenuation compared to the Al–Cu alloys, and the thickness of the crucible cavity where X-rays penetrate through was 1 ± 0.05 mm. The Al–10 wt% Cu alloy was pre-machined in order to fit into the cavity of crucible. The alloy was then melted and stabilized at 660 ± 10 °C. The temperature

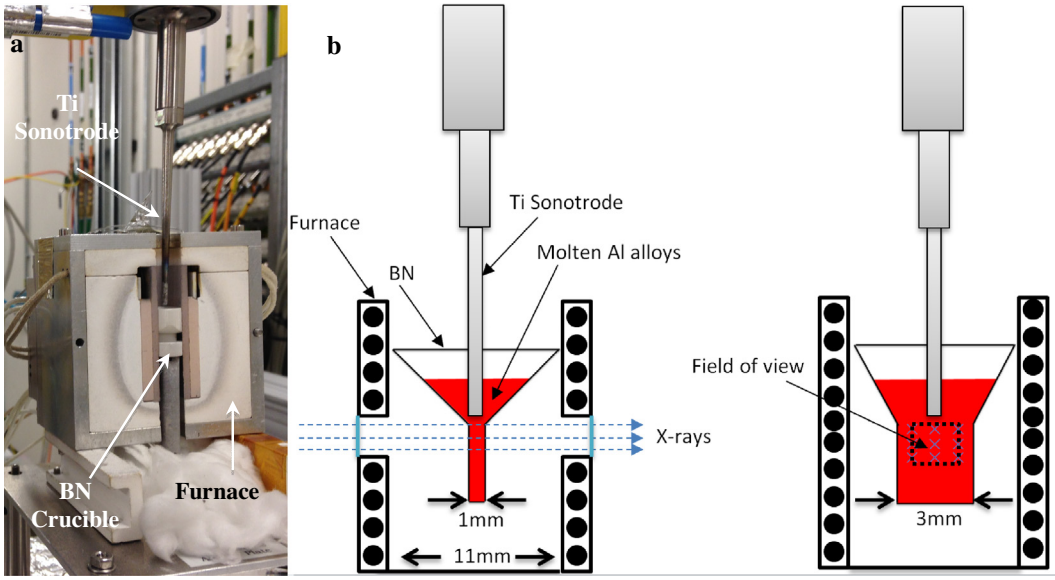

Fig. 1. Experimental test rig: (a) sectional view of the experimental set up and (b) schematic representation of the test rig with some key dimensions of the furnace and BN crucible used for the ultrasonication in the beamline. The high density X-ray beam is delivered through the X-ray tube to the molten sample placed inside the crucible. The camera on the opposed side captures the real time event of ultrasonication and delivers images to the super-computer for further analysis.

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