Ultrafast synchrotron X-ray imaging of multiphase fluid flow in metal solidification under ultrasound

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Introduction

Applying ultrasonic waves in a liquid medium creates an alternating acoustic pressure field. When the pressure is above a certain threshold, ultrasonic bubbles and acoustic streaming flow are produced in the liquid. The ultrasonic bubbles vibrate according to the alternating pressure, grow, coalesce and finally collapse, creating local shock waves with high pressure and temperature in the nearby region. This is commonly known as ultrasonic cavitation. These are highly dynamic nonlinear phenomena and when they occur in liquid metal, especially during the solidification processes, the heat/mass transfer, fluid flow and ultimately the microstructures of the solidifying metal are affected. Ultrasound processing of metal alloys is a promising green technology for metal industry. However many fundamental issues in this field are still not fully understood because the difficulties in direct observation of the interactions between ultrasound and liquid metal and solidifying phases during the solidification processes.

1. Methods

We used the dedicated ultrafast synchrotron X-ray Imaging capability available at sector 32-ID-B of the Advacned Photon Source (APS) to study in-situ the dynamics of ultrasonic bubbles and enhanced acoustic flow in liquid and semisolid state of a Bi-8%Zn alloy. Sector 32-ID-B is an undulator source designed to utilise the 500 ns X-ray pulse delivered by the storage ring of APS when operated in a hybrid mode. Using such short X-ray pulse, an effective image acquisition rate of up to 271,554 fps with a spatial resolution of 1 μm/pixel can be achieved [1]. Using a special in-situ ultrasound solidification apparatus [1], the highly dynamic behaviour of ultrasonic bubble implosion in liquid metal, the multiphase metal flow containing bubbles and particles, and the interactions between ultrasonic waves and semisolid phases during solidification of metal were studied systematically. Figure 1 shows the oscillation and implosion of a bubble in a single wave period. Figure 2 shows a series of image sequences captured using 5413 fps at 0.5, 2.5, and 4.5 mm below the sonotrode tip (a tip diameter of ~0.3 mm and 30 kHz, 20 W ultrasound power), respectively. The images show that, after applying ultrasound, the Zn particles were shaken" off the tip and flew downward together with ultrasonic bubbles as shown from Figure 2a-2 to Figure 2a-4. The behaviours of the bubbles and particles further away from the sonotrode tip were imaged separately using the identical melt conditions and ultrasound input power. The image sequences taken at the different distances away from the sonotrode tip allowed systematic and statistical datasets to be extracted from the images for studying quantitatively the dynamic behaviours of the bubbles, the particles and the enhanced metal flow at different locations. The experimental results were complimented by numerical modelling. The interaction and fragmentation of solidifying Zn phases by cyclic fatigue due to the oscillating bubbles and ultrasound enhanced acoustic flow were clearly revealed for the first time [2]. The experimental observations agree very well with the theoretical calculations.

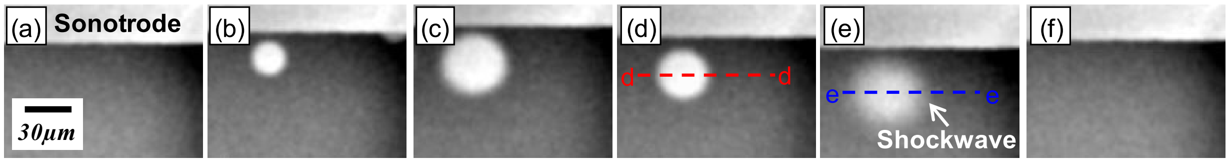

Figure 1. Six consecutive images, showing the oscillation and implosion of a bubble in a single wave period (an exposure time of 500 ns, and a time interval of 7.4 μs between the consecutive images).

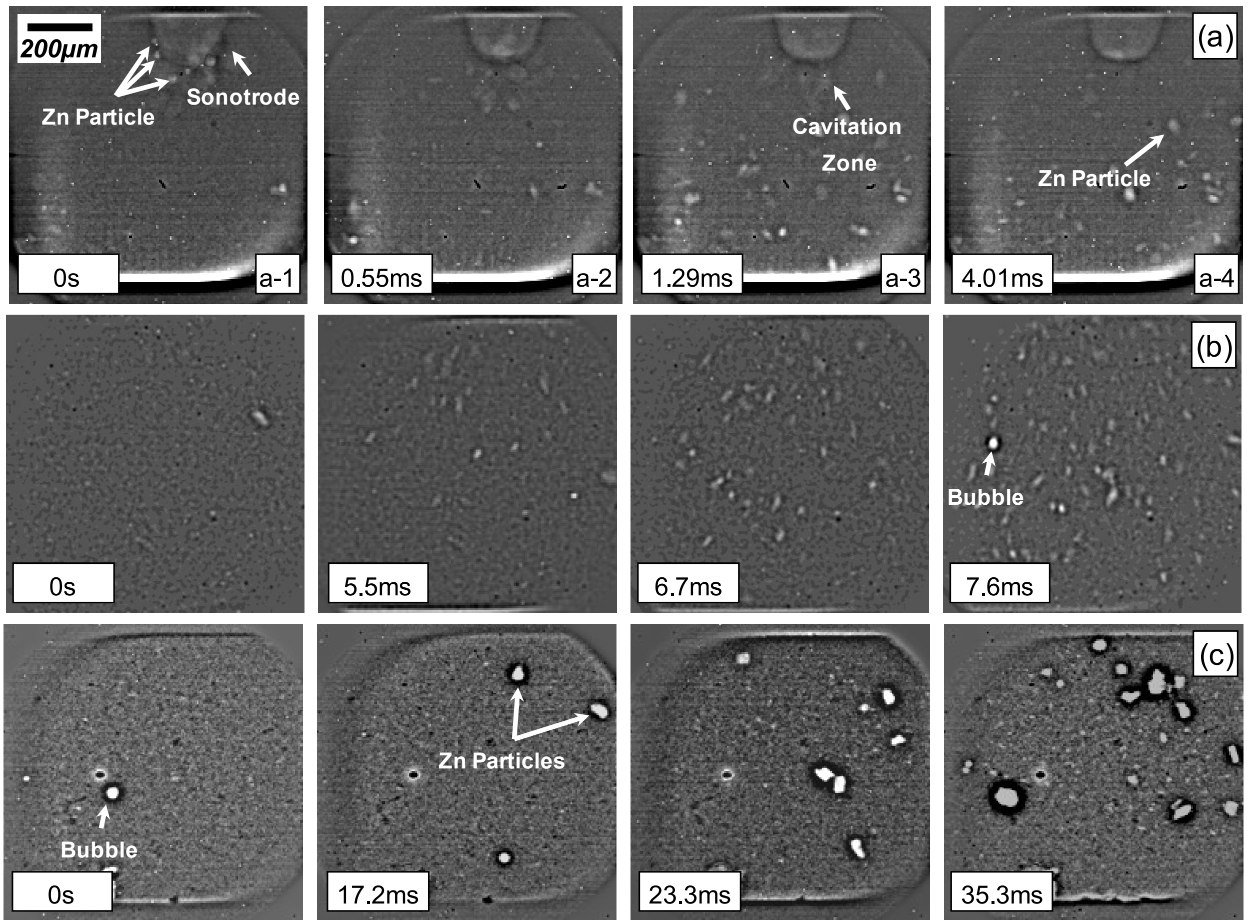

Figure 2. A series of images captured in liquid Bi-8 wt. %Zn alloy with an ultrasound power of 20 W at APS using 5413 fps. The images were taken at (a) 0.5 mm, (b) 2.5 mm, and (c) 4.5 mm respectively below the sonotrode tip.

References

[1] D. Tan, T. L. Lee, J. C. Khong, T. Connolley, K. Fezzaa, J. Mi, High speed synchrotron X-ray imaging studies of the ultrasound shockwave and enhanced flow during metal solidification processes, Metallurgical and Materials Transactions A, Vol. 46 (2015), 2851 – 2861.

[2] B. Wang, D. Tan, T. L. Lee, J. C. Khong, F. Wang, D. Eskin, T. Connolley, K. Fezzaa, J. Mi, Ultrafast synchrotron X-ray imaging studies of microstructure fragmentation in solidification under ultrasound, submitted to Acta Materialia in July 2017.