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Original Article

Optimizing high-volume ultrasonic melt degassing using synchronized kinematic translation

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ABSTRACT

Ultrasonic vibration is a physical processing technique that has been gathering support as an environmentally friendly approach to degas light alloy melts. Since metallic sonotrodes promote melt inclusions due to erosion, ceramic sonotrodes have also been shown as a viable solution for ultrasonic melt degassing in industrial scales. This study shows that resonant ceramic sonotrodes are characterized by a complex low-amplitude radial eigenmode, while particle image velocimetry reveals that their efficiency depends on the angular direction. An approach based on synchronized kinematic translation was designed to optimize the degassing efficiency in ultrasonic approaches, assuring its angle with higher cavitation is always facing the center of the crucible. Results show that this approach can reach lower degassing thresholds ($H_{\min} = 0.13 \text{ ml/100 g Al}$) at higher degassing rates, relatively to both Argon inflation ($H_{\min} = 0.22 \text{ ml/100 g Al}$) and static Ultrasound ($H_{\min} = 0.18 \text{ ml/100 g Al}$) methods. An enhanced grain refinement further supports the hypothesis that promoting a synchronized kinematic translation enhances the ultrasonic degassing efficiency. Considering these results, this approach is suggested as a reliable route to implement efficient ultrasonic degassing techniques in industrial light alloy melt treatment.

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1. Introduction

Aluminum and its alloys are a current choice within popular metallic materials. They have a wide range of applications due to their high strength to weight ratio and their ability to be recycled makes them relevant to industries due to current environmental concerns.

One of the most promising routes to process these alloys is their melt treatment by ultrasonic vibration [1]. Commonly

used for degassing and grain refinement purposes [2], this technique is performed applying acoustic cavitation and streaming within the melt [3]. Recently, we have shown that ultrasonic melt treatment may be used to optimize the heat treatment in these alloys (e.g. AA7075) by enhancing precipitation hardening and reducing peak-ageing times [4]. These methods can also be considered sustainable, given their capacity to improve the overall physical and mechanical (i.e. static and dynamic) properties [4–6] with a reduction or even

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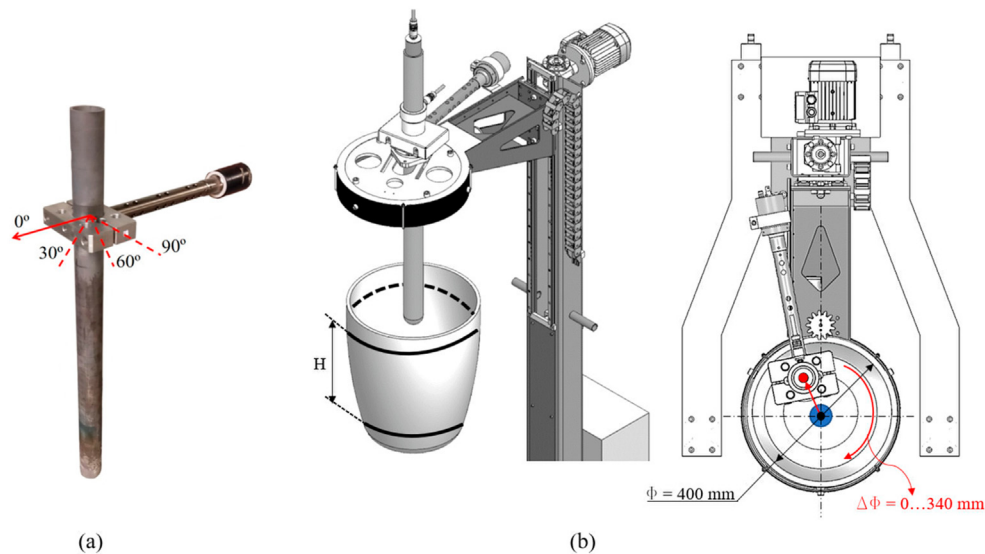


Fig. 1 – Detail of (a) SiAlON sonotrode and (b) synchronized kinematic translation apparatus.

without the use of potentially environmentally harmful additives, such as chemically refining and/or modifying (e.g. Al–Ti–B, Al–Sr, Al–Sc) master alloys and purge gases (e.g. Argon, Nitrogen, etc).

Concerning the grain refinement by ultrasonic melt treatment, even though it is a widespread technique that has been successfully applied in numerous alloys (e.g. [7–10]), the governing mechanisms that control its effect are still being currently detailed [11]. These techniques are beneficial to control the nucleation and refinement of intermetallic compounds (IMCs) [12], preventing the low toughness and ductility by their coarsening into hazardous shapes [13]. Additionally, refined IMCs may improve mechanical properties by acting as reinforcements in metal matrix composites (MMCs) [14,15], and also act as heterogeneous nucleant promoting grain refinement [16]. Wang et al. [17] studied the effect of cavitation in the fragmentation of primary crystals formed in Al alloys. Priyadarshi et al. [11] have studied the fragmentation mechanism of primary IMCs by cavitation in ultrasonically treated melts, concluding that IMC fracture is promoted by the combination of shock waves from the collapsing bubbles and low cycle fatigue followed by brittle failure due to propagating shock waves.

As hydrogen has significant solubility in Al melts [18,19], the cavitation that is promoted by ultrasonic melt treatment is also suggested as an effective method for degassing purposes [2]. Although the ultrasonic degassing of liquids was introduced in the 1930's [20], its research and application in light alloys was pioneered by G.I. Eskin in the 1960's [21]. Bubble implosion from cavitation and shock pressure fields has been thoroughly researched (e.g. [22–28]), and it is widely accepted that their rapid growth and collapse during the ultrasonic compression cycles yields fast jets and elevated in-situ hydrodynamic impact pressures [29–31]. This approach is a sustainable alternative to purge gases (e.g. Argon or Nitrogen) [32,33], hexachloroethane (C_2Cl_6) tablets [34], among others [35], being efficient to degas small melt volumes quickly.

Characterizing these effects is inherently complex due to the handling of liquid melts (i.e. high temperature) and melt opaqueness [36]. These limitations have been addressed by the *in-situ* observation of organic transparent liquids [37,38]. Water, for instance, has been shown to display an approximate kinematic viscosity and Newtonian behavior to Al melts, thus, it hinders an equivalent analysis in terms of cavitation nucleation and bubble dynamics [2,39,40]. Commander and Properetti [41] have modeled bubble propagation and its non-linear behavior by a computed tractable formulation, including the complex wave number in a Helmholtz equation. In the latest developments of these approaches, Lebon et al. [42] have applied Louisnard's [43] model for acoustic streaming and Trujillo's [44] non-linear Helmholtz equation to Direct-Chill Casting of 6XXX series Al alloys with ultrasonic treatment to study the acoustic streaming patterns in the sump. Lebon et al. model has been previously validated in water [45], while Louisnard's [43] work has shown a good correlation with Particle Image Velocimetry (PIV) experiments in water medium.

Streaming due to ultrasonic acoustic excitation in a fluid medium is known to be dependent on the acoustic power and forms a conical jet flow pattern that displays a recirculating flow in the vicinity of the cavitation zone [46–48]. Numerous researchers have worked on experimental techniques to understand cavitation and cavitation induced streaming in liquids. Recently, Grilo et al. [49] studied the dispersion of microparticles in water by ultrasonic excitation using PIV. Synchrotron X-ray radiography is also a trending technique for these purposes, having been successfully employed by Mirhanage et al. [50] to detail the distribution, radius growth and density of cavitation bubbles in an Al–10Cu alloy. Wang et al. [51] also characterized the real-time fragmentation and refinement of Al_2Cu phases in an Al–35Cu alloy. Understanding these streaming paths within a liquid melt is fundamental to optimising the design and efficiency of ultrasonic degassing and refinement techniques. Additionally, it

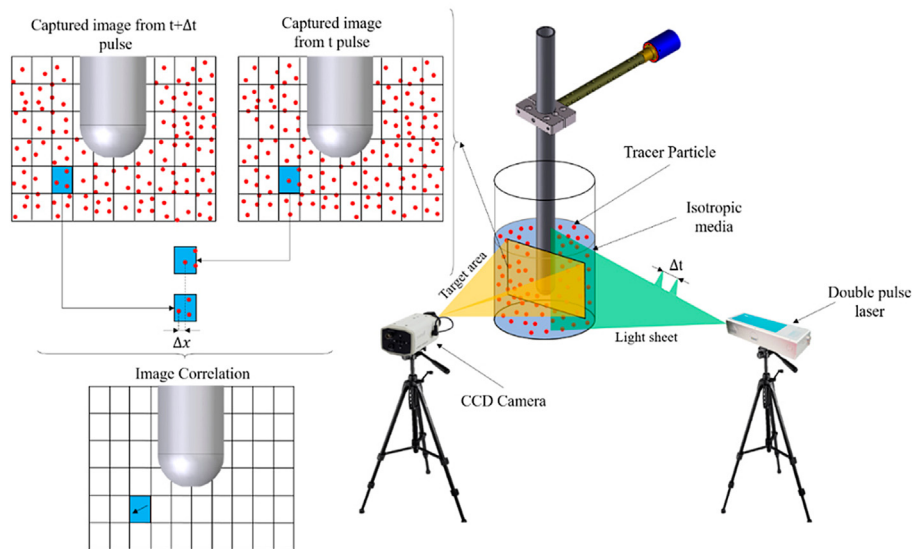


Fig. 2 – PIV setup for water flow field of water analysis.

is a relevant issue to allow the transition of these processes into industrial scales, e.g. studies have shown that rotational and vertical translation of ultrasonic sonotrodes is beneficial for the overall degassing and grain refinement [52].

The most relevant challenge in the industrial implementation of these techniques is the use of metallic sonotrodes. These are known to generate erosion and inclusions by prolonged exposure to reactive melts (e.g. Ti and Nb alloy sonotrodes in Al melts) [53–57]. This is currently addressed by the use of ceramic based (e.g. SiAlON) sonotrodes [58], which may be safely used at high temperatures with low amplitude resonant regimes. We have shown that these sonotrodes display complex radial eigenmodes that influence the overall performance of the melt treatment [59]. Recognizing that the vibration amplitude is known to have a crucial impact on acoustic streaming [60], ceramic sonotrodes tend to compensate their low-amplitude with larger surface areas that generate cavitation. This study details the influence of complex radial vibration in the directionality of these sonotrodes. The results demonstrate a feasible approach to enhance degassing efficiency by performing synchronized kinematic translation, ensuring that the ceramic sonotrode permanently induces cavitation in its most efficient configuration.

2. Methodology

2.1. Overall description of the proposed method

Multi-frequency-mode-modulated technology ultrasonic energy ($P = 600$ W, electrical power) was driven from a PIEZO transducer by an acoustic waveguide (35 mm diameter and 420 mm length) clamped to a SiAlON tube (60 mm diameter and 1200 length), according to Fig. 1 (a). The ultrasonic sonotrode was designed to resonate at 20.2 ± 0.4 kHz in a low-amplitude radial eigenmode to promote a well distributed Lamb-wave propagation in the walls through the overall

length [59]. As detailed in Fig. 1 (a), the overall characterization of the sonotrode and the streaming that is able to generate was performed in the 0° , 30° , 60° and 90° relatively to the excitation source. Considering recent findings on the complex vibration profiles in the radial eigenmodes of ceramic sonotrodes [59], the ultrasonic system was initially introduced in a water medium with tracer particles to study the directionality of the ultrasonic vibration propagation on the fluid medium using particle image velocimetry (PIV).

The SiAlON sonotrode was then introduced in a light alloy melt, taking into account the findings of the PIV tests, optimising the overall ultrasonic melt treatment efficiency by using synchronized kinematic translation. The ceramic sonotrode was assembled into a ring guide that inputs a synchronized kinematic translation movement (Fig. 1 (b)), with a circular displacement ($\Phi = 300$ mm) while submerged ($H = 250$ mm). The performance of the standard ultrasonic degassing approach was compared by operating the ring guide kinematic movement (i.e. static) and placing the sonotrode in the geometrical center of the crucible.

2.2. Particle image velocimetry

Due to the complex vibration in ceramic sonotrodes radial eigenmodes, the directionality of the ultrasonic vibration propagation in a fluid medium was tested using 2D PIV. The PIV setup (Dantec Dynamics-145) measurements were carried out in a transparent cylindrical container with $\varnothing 250 \times 450$ mm volume of water, where the ceramic sonotrode was inserted (250 mm) in the fluid (Fig. 2). Aluminum particles ($15 \mu\text{m}$ and $\rho = 2700 \text{ kg/m}^3$) were used to scatter the emitted laser light toward the CCD camera, placed in a normal position to the double plus laser system, which emits two independently controlled beams with a pulse energy of 145 mJ at a wavelength of 532 nm. The camera was equipped with a 50 mm Zeiss lens and set at an f-number = 1.4.

Dynamic Studio software was used for data acquisition and further post-processing of the images, wherein the digital

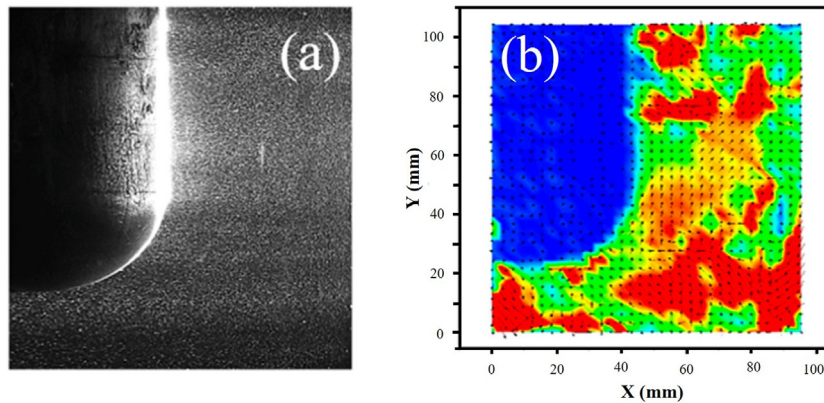


Fig. 3 – PIV image processing procedure: (a) Spatial distribution of acoustic flow structures and (b) mapped streamline velocity amplitude (Note: The region with low velocity magnitude, the blue color represents the sonotrode surface). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

PIV recording was partitioned into interrogation areas using auto- and cross-correlation statistic techniques (Fig. 2). The local displacement vector measures two consecutive images with a defined time frame (Δt). An homogenous transition was assumed for particles within one interrogation area at each time frame (Fig. 3 (a)), while particle translation and flow visualization is performed by recording both emitted laser light pulses. The tracer particles' velocity amplitude and velocity vector map were also integrated (Fig. 3 (b)). This procedure was repeated for 0° , 30° , 60° and 90° , relatively to the waveguide (see Fig. 1 (a)) to study the directionality of the ultrasonic excitation.

2.3. Ultrasonic melt treatment and casting process

A SiC crucible with a capacity for 20 kg of Al alloy was introduced in an electric resistance furnace (Fig. 4) and pre-heated (400°C) for 1 h to remove residual humidity. AlSi9Cu3(Fe) alloy, previously degreased and dried, was inserted in the crucible. The temperature was then raised to $720 \pm 10^\circ\text{C}$ to melt the alloy. After melting, the alloy was allowed to homogenize for 15 min and the melts were degassed with the approaches described in Table 1. Samples were collected from the melts for different degassing times (1, 3, 5, 7 and 9 min) while the melt was kept isothermal ($720 \pm 5^\circ\text{C}$). After the different degassing processes, the melt was gravity cast into a stainless steel cup to be subjected to a Reduced Pressure Test (RPT) Method ($p = 80\text{ mmHg}$) and expand dissolved hydrogen during solidification. Samples were also cast right after the homogenization period to determine the initial volume of dissolved hydrogen and compare the efficiency of the degassing processes. Each degassing approach was repeated five times to estimate the process repeatability.

Tensile specimens were produced by gravity casting the melts that were degassed for 9 min into a pre-heated ($300 \pm 10^\circ\text{C}$) steel die with a cylindrical cavity ($\varnothing 18\text{ mm} \times 150\text{ mm}$). The cast cylindrical specimens were machined in a CNC lathe to obtain tensile testing specimens (Type B) according to the ISO 6892 standard. Tensile samples (5 for each processing condition and in their non degassed state, a total of 20 samples) were tested in an INSTRON 8874 universal testing equipment with a 0.1 mm/s displacement rate. The strain in the samples was measured with a mechanical strain gauge and loads were monitored by the equipment load cell.

2.4. Metallurgic sample analysis

Vacuum cast samples were sectioned vertically and polished with SiC abrasives down to an $11\text{ }\mu\text{m}$ granulometry. These samples were then observed to characterize their porosity, measuring/counting the pores and their hydrogen volume fraction. Sample polishing was then finished using a $1\text{ }\mu\text{m}$

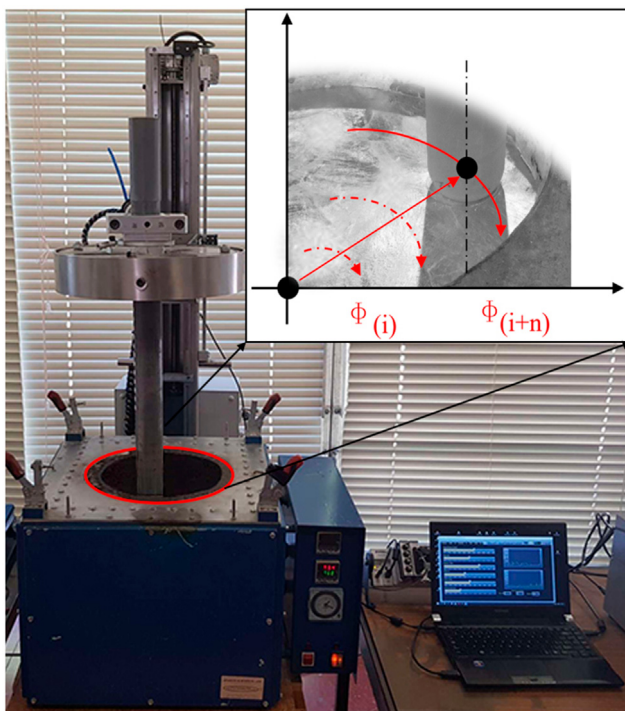


Fig. 4 – Experimental apparatus for the ultrasonic ceramic sonotrode translation.

Table 1 – Description of the tested degassing approaches.

Melt	Degassing approach	Description
1	Argon inflation	Argon gas inflation at the bottom of the crucible with a impeller (100 rpm).
2	Ultrasonic (US)	Pre-heated ($720 \pm 10^\circ\text{C}$) ceramic sonotrode was dipped (250 mm) in the melt at the geometrical center of the crucible.
3	Ultrasonic + Translation	Pre-heated ($720 \pm 10^\circ\text{C}$) ceramic sonotrode was dipped (250 mm) in the melt and with slow (5 mm/s linear velocity) circular translation movement (150 mm radius).

diamond solution to prepare them for microscopic analysis (Leica DM2500M). This analysis allowed the visualization of microstructure of the aluminum samples to determine the α -grains size and shape.

2.5. Acoustic sensor - cavitometer

A Kingstate KPSG-100 piezo was used as an acoustic sensor to monitor the cavitation in the melt. This piezo disk is fabricated with a ceramic layer (23.5 mm diameter and 1 mm thickness) that is deposited over a thin brass disk for high vibration sensitivity in a wide frequency range (up to 60 kHz). This disk was assembled into a molybdenum rod (2 mm diameter and 1000 mm in length) that allows the insertion of the sensor in the locations.

3. Results

3.1. Directionality of the ultrasonic propagation

PIV results during the water sonication procedure are plotted and presented in Fig. 5 (a) to (d), showing the streaming that is created by cavitation region pulsation as denominated by Wang et al. [3]. According to Tzanakis et al. [40] and Yamamoto et al. [60], water has the closest cavitation properties with liquid aluminum and the velocity of acoustic streaming in water is equivalent to aluminum melts. The acoustic cavitation and streaming phenomena quantification at the vicinity of the different tested directions (0° to 90° , according to the model Fig. 1 (a)), after initial instantaneous moment considered as $t = 0 \mu\text{s}$, were subdivided into $50 \mu\text{s}$ time frames, the typical time period for a single oscillation to yield an aluminium $\sim 100 \mu\text{m}$ cavitation bubble as reported by Xu et al. [29]. The observed behavior is also in accordance with Liu et al. [36], showing that significant cavitation is nucleated and dispersed in the hemispherical cap of the sonotrode.

The fluid in the sonotrode vicinity was pushed into a transversal laminar flow and forced into an irregular fluctuation turbulent flow regime. The resultant flow velocities suggest that the internal pressure is enough to generate cavitation while maintaining a linear bubble oscillation, which is according to the model of Yamamoto et al. [31]. Furthermore, this behavior is in accordance with bubble implosion and oscillation, as reported by Wang et al. [10]. Thus, during the turbulent regime, the velocity vectors dynamically change their magnitude. The continuous ultrasonic vibration does not allow the return to a laminar flow, however, this is more prominent in Fig. 5 (a), (b) and (d) (directions 0° , 30° and 90° , according to Fig. 1 (a)). Both

large areas with high flow velocity and quasi-static (i.e. low velocity) are detected in these frames. Figure 5 (c), directions 0° , 30° and 90° , according to Fig. 1 (a), shows that the net average flow velocity is relatively low.

To observe the dynamic distribution of fluid, the entire plane of the vector angle was mapped according to Fig. 6. Three zones of vertical positional of particles, including (i) the vicinity of the sonotrode (X_1), (ii) middle of the container (X_2) and (iii) the vicinity of the container wall (X_3), were considered.

Figure 7 shows the histograms for positional/vector field gradient profiles with the orientation of the velocity measurements for vector angle distribution density. These plots were sectioned into two zones in which the downward ($-\pi$ to 0 rad) and upward (0 to π rad) particle displacements are highlighted.

The tracking of the distribution of vector angles evidence that there is a clear dependence on the directionality of the sonotrode and impact on upward or downward displacements. While the majority of microparticles in the 60° and 90° sonotrode direction (respectively, Fig. 7 (c) and (d)) tend to display an upward displacement, in the 30° direction, they present the opposite behavior (i.e. downward displacement) (Fig. 7 (b)). In the principal sonication direction (i.e. 0°), a hybrid behaviour is evident, with a clear transition from an upward to a downward displacement as the flow is more distant to the sonotrode (i.e. $X_1 \rightarrow X_2 \rightarrow X_3$). These results are in agreement with Xu et al. [29] hypothesis that low ultrasonic intensities oscillate for multiple acoustic cycles while increasing their radius and reaching their maximum size. However, according to Tzanakis et al. [39], there can be affected by a pronounced shielding effect and acoustic damping in the Al melt. The PIV results confirm that the sonotrode displays has a directional dependent behavior and, consequently, this influences the degassing through cavitation within the full volume of the melt.

3.2. Light-alloy melt degassing

Figures 5 and 7 show that there is an effective dependence on velocity vector magnitude and angle, influenced not only on the complex vibration of the sonotrode as reported in previous studies [59], but also with the sonotrode direction and distance in the fluid medium. These aspects are expected to have a profound impact in the melt degassing efficiency by ultrasonic approaches. It is predictable that using a static sonotrode (i.e. without translation motion) could reduce the distribution of acoustic pressure in the melt and, thus, the ability to remove dissolved hydrogen.

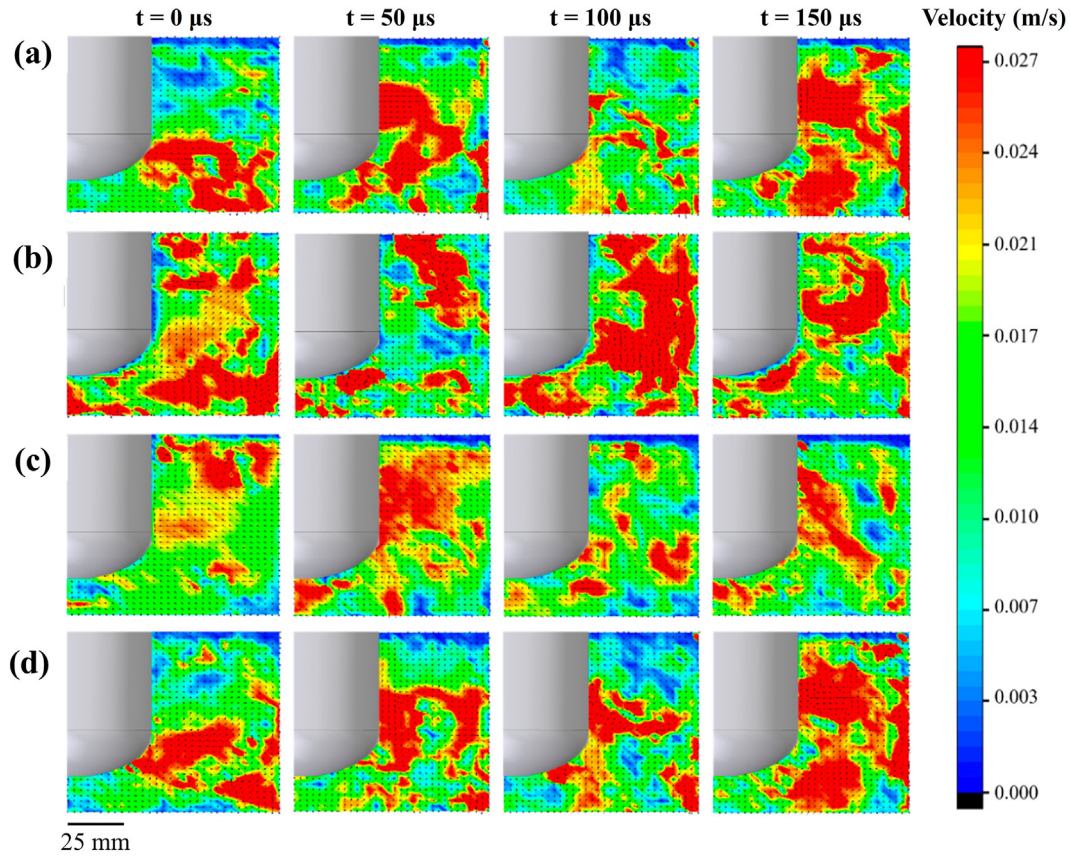


Fig. 5 – Time evolution of velocity streaming contours PIV experiments in the tested directions: (a) 0°; (b) 30°; (c) 60°; and (d) 90°.

For comparison purposes issues, Fig. 8 highlights the non-degassed alloy pores in samples that were solidified under vacuum conditions (RPT test). Figure 8 may then be compared with samples degassed with different approaches and time

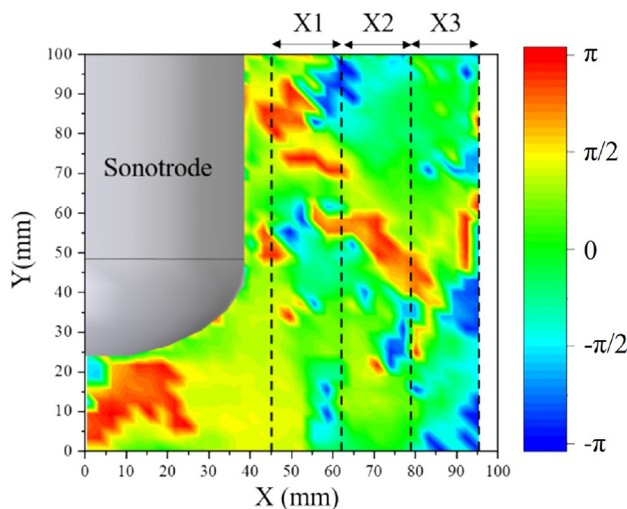


Fig. 6 – Example of vector field gradient during sonication procedure (Red/blue color, i.e. positive/negative values mean upward/downward displacements). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(Table 2). It is clear that the degassing approach substantially impacts the volume fraction of porosity in the cast samples.

Table 3 presents the average specific density within the Al alloy (i.e. solid fraction) and pore count in the samples degassed under different regimes and solidified in vacuum. As expected, it is clear that all means of degassing generate a positive effect in the alloy, as they reduce the pore count and increase the overall solid fraction.

As expected, the methods have different degassing efficiencies. For instance, considering the volume of Al melt treated, the Argon method is apparently less efficient than the ultrasonic method. Comparing the adopted ultrasonic degassing approaches, it is notorious that the synchronized kinematic translation method is able to generate an increase in the overall solid fraction and, therefore, its implementation may be beneficial.

Figure 9 presents the evolution of dissolved Hydrogen in the melts by the different approaches, apparently display different degassing efficiencies.

By the experimental results shown in Fig. 9, it is proposed that an exponential decay function may describe the dependence of dissolved gas (VG) with degassing time (Eq. (1)), where $H_{\min}$ is the degassing threshold, while A and B are decaying constants that control the rate at which the threshold is reached. The correlation with the proposed functions and the low values of standard deviation also attest the repeatability of the processes.

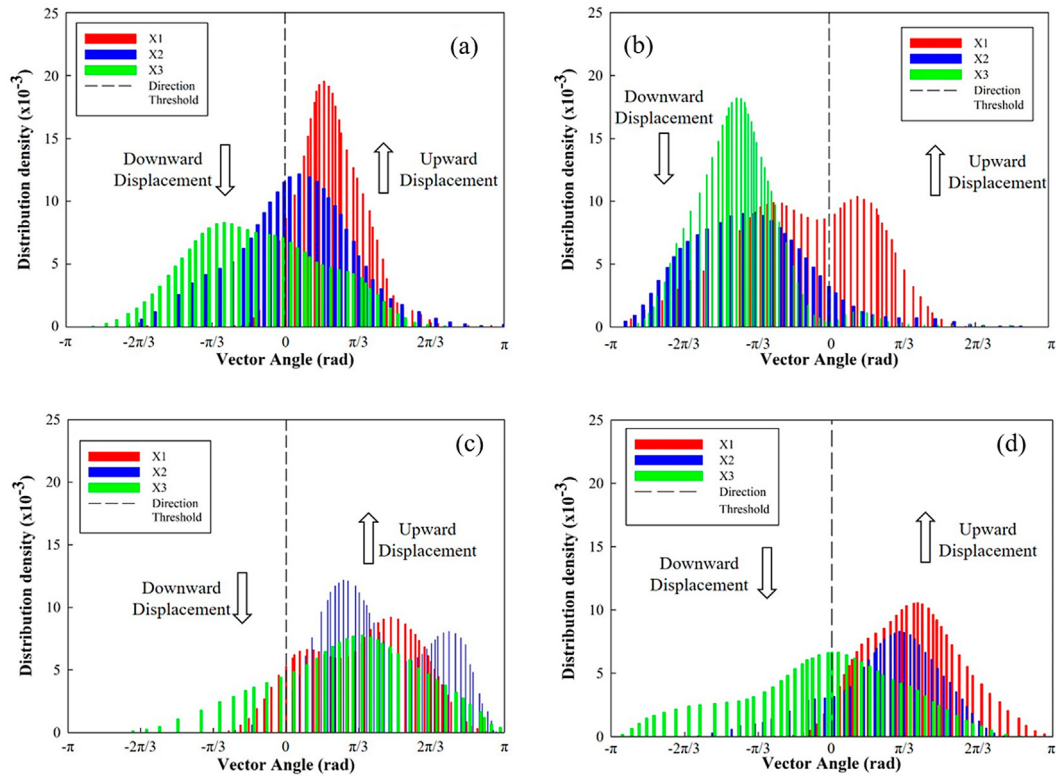


Fig. 7 – Histograms of vector angle distribution density in the measured points dependent on sonotrode orientation: (a) 0°; (b) 30°; (c) 60°; and (d) 90°.

$$VG = H_{\min} + A \cdot e^{-Bt} \quad (1)$$

This is aligned with the classic hydrogen concentration in the melt (H/H_0 , Eq. (2)) as a function of purging time (t), where k is the mass transfer coefficient, ρ is the melt density, S is the surface area of the formed bubble and M is the melt weight [61]. The inflation of Argon in Al melts forms bubbles, with a surface area (Eq. (3)) that depends on their radius (r), residual time in the melt (τ) and molar flow rate of inert gas ($\dot{G}$), which purge fine dissolved hydrogen and degas the melt [61,62].

$$\left[\frac{H}{H_0} \right] = e^{-k\rho S/Mt} \quad (2)$$

$$S = \frac{3\dot{G}\tau}{r} \quad (3)$$

According to this analysis, it is established that the Argon approach is less efficient, as it tends to have a higher degassing threshold ($H_{\min, \text{Argon}} = 0.22 \text{ ml/100 g Al}$). Results show that the use of kinematic translation in the ultrasonic approach is able to enhance the overall degassing efficiency ($H_{\min, \text{US} + \text{translation}} = 0.13 \text{ ml/100 g Al}$), relatively to an approach in which the ultrasonic sonotrode is static ($H_{\min, \text{US}} = 0.18 \text{ ml/100 g Al}$). Comparing both ultrasonic degassing methods, it is suggested that the synchronized kinematic translation is more efficient in the transition of acoustic power to higher melt volumes.

Ultrasonic melt vibration generates cavitation by a high frequency local pressure (p) shifting between a minimum and maximum values according to Eq. (4), depending on the atmospheric pressure (p_0), wave velocity (c) and wave energy density (I) [63]. This cavitation nucleates bubbles that grow

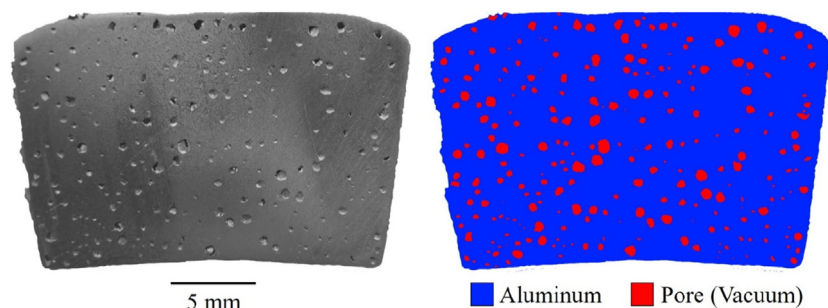
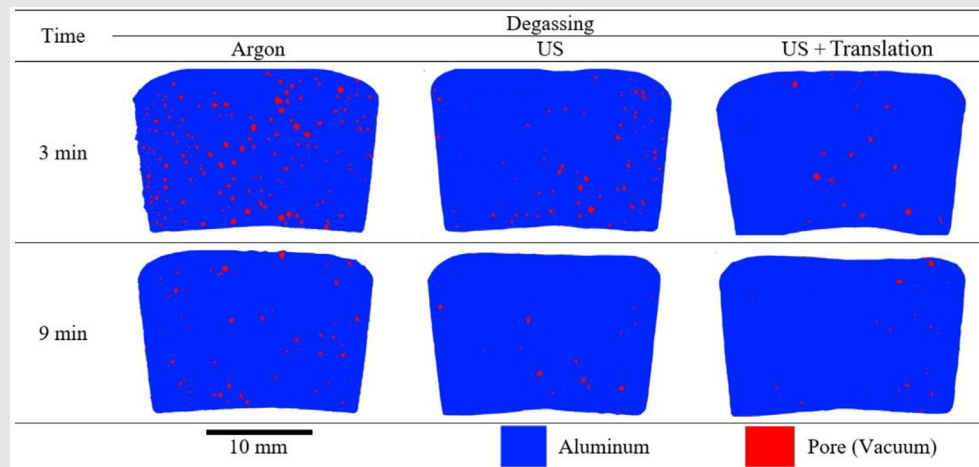


Fig. 8 – Porosity in vacuum solidified sample without degassing.

Table 2 – Porosity in vacuum solidified samples with different degassing approaches.

with the diffusion of dissolved hydrogen, coalescing to form larger bubbles and float to the surface of the melt where the dissolved gas escapes [20,36,64]. Thus, the use of a ceramic sonotrode increases the wave energy density due to its high active surface (e.g. Figure 5). Unlike metal-based sonotrodes, characterized by a high-powered and concentrated cavitation source, ceramic sonotrodes can promote cavitation in large melt volumes by vibrating in a wide radial superficial area.

$$p_{(max:min)} = p_0 \pm \sqrt{2\rho cI} \quad (4)$$

Due to the value of the decaying constants (A and B), the experimental results (Fig. 9) show the threshold values are reached much quicker (i.e. higher degassing rate) when the synchronized kinematic translation is used. For instance, the value $H = 0.25 \text{ ml}/100\text{g}_{\text{Al}}$ is reached by the Argon, US and US + Translation approaches, respectively, in a 9.50 min, 1.5 min and 1.2 min time frames. This means that the use of synchronized kinematic translation is an effective route to reduce degassing time in industrial scale foundries. This is proposed to be attributed to its superior performance due to an enhanced distribution of cavitation in the entire volume by

two factors: (i) the high intensity acoustic excitation in the vicinity of the sonotrode generates cavitation; and (ii) the lower intensity of acoustic excitation in the neighbouring volume of the sonotrode generates streaming that distributes the cavitation bubbles. The synchronized kinematic translation allows these events to occur in the full volume of the crucible.

Ultrasonic melt treatment is frequently used as a physical melt processing for grain refinement [65,66]. However, due to its use for degassing purposes, ultrasonic degassing was performed at a relatively high temperature (720 °C) which may compromise an efficient ultrasonic grain (i.e. physical) refinement. It is known that cavitation and streaming below *liquidus* fragments and redistributes dendrites [4] and melt temperatures above *liquidus* reduce the nuclei survival time (i.e. fading), thus, effectively decreasing the probability of nucleation and the number of grains that will result in the final cast microstructure [67]. However, Puga et al. [7] have shown that ultrasonic melt treatment may increase the liquidus temperature, mitigating this effect. Still, the samples with ultrasonically treated melt display a moderate grain refinement. The presented micrographs can evidence this behavior, as the Argon degassed micrograph in Fig. 10 (a) displays large dendrites, while Fig. 10 (b) and (c) show globular and rosette-like α -Al grains, highlighting some moderate grain refinement promoted by the ultrasonic melt treatment.

According to Table 4, it is shown that as-cast samples (i.e. not heat treated) with ultrasonic degassed melts display higher values of yield and ultimate tensile strengths for the gravity cast AlSi9Cu3(Fe) alloy. They are also able to support higher deformation without fracture, i.e. higher extension than Argon degassed melts. Additionally, the moderate grain refinement that is observed in the samples with ultrasonically treated melts seems to be enhanced when synchronized kinematic translation is performed by a Hall-Petch mechanism and reduction in porosity. The low values of standard

Table 3 – Volume fraction and pore count in vacuum solidified samples with different degassing approaches.

Degassing	Porosity in Samples Solidified in Vacuum	
	δ^*/δ_0 - Specific density (%)	Avg. Pore Count (–)
0 min No degassing	89.5 ± 5.1	258 ± 32
3 min Argon	95.0 ± 4.3	172 ± 16
US	98.7 ± 0.3	39 ± 18
US + Translation	99.3 ± 0.4	80 ± 15
9 min Argon	98.0 ± 1.5	60 ± 21
US	99.1 ± 0.2	28 ± 14
US + Translation	99.6 ± 0.3	34 ± 15

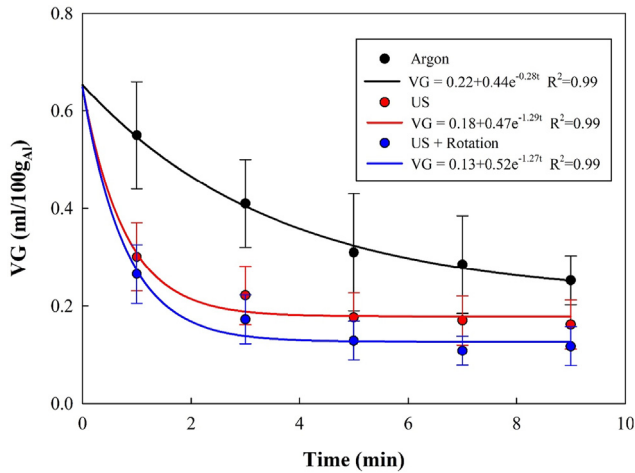


Fig. 9 – RPT test results with different degassing approaches.

deviation from samples that originated from different castings suggest that the adopted processes are highly repeatable.

Considering the static approach (i.e. sonotrode placed in the center of the crucible), it is proposed that the sonotrode directionality influences the ceramic sonotrode radial cavitation range. According to Fig. 11, cavitation is not promoted uniformly, as there is a clear increase in cavitation resultant for the eigenfrequency harmonics for angles that are aligned with the principal vibration axis (i.e. 0°, Cavitometer 1 – Fig. 11), as displayed in Figs. 5–7. Tzanakis et al. [40] reported that both sharp peaks that correspond to harmonics of the driving frequency and sub-harmonics are expected to represent the dynamics of cavitation bubbles. When the angle

Table 4 – Static mechanical properties of samples degassed with different approaches.

Mechanical Property	Melt Processing		
	Argon	US	US + Translation
σ_Y – Yield Strength (MPa)	187 ± 14	198 ± 8	206 ± 10
σ_{UTS} – UTS (MPa)	213 ± 12	235 ± 7	256 ± 8
ϵ – Extension (%)	0.5 ± 0.2	0.7 ± 0.1	0.9 ± 0.1

tends to deviate from this principal ultrasonic vibration angle (i.e. 45°, Cavitometer 2 – Fig. 11), the cavitation that results from the eigenfrequency harmonics tends to be suppressed, implying a reduction in the melt volume that is effectively

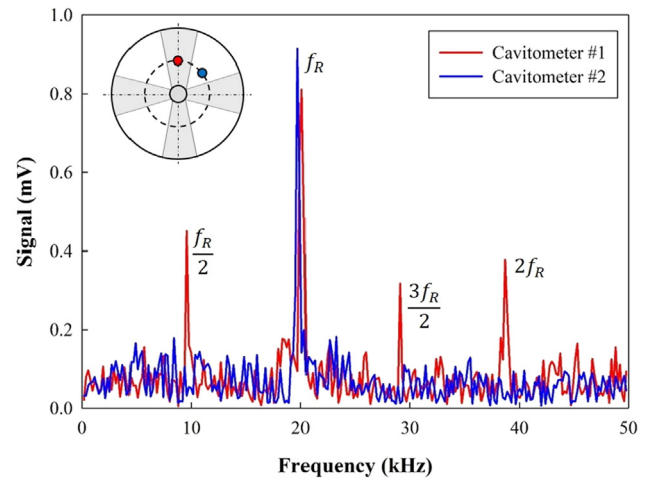


Fig. 11 – Cavitation in the crucible using the static ultrasound melt treatment approach.

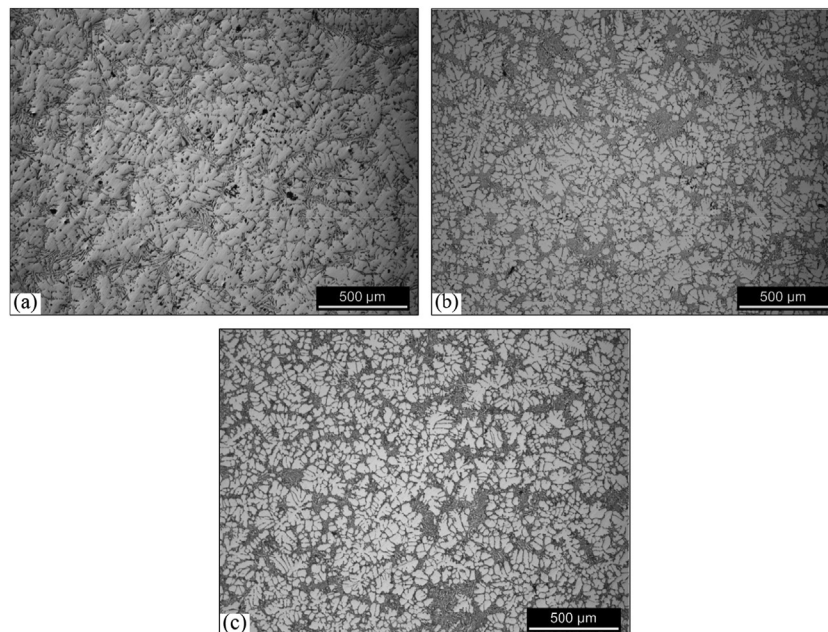


Fig. 10 – Microstructures of samples degassed with: (a) Argon – Dendritic; (b) Static ultrasound – Rosette and globular grains; and (c) Ultrasound + translation - Rosette and globular grains.

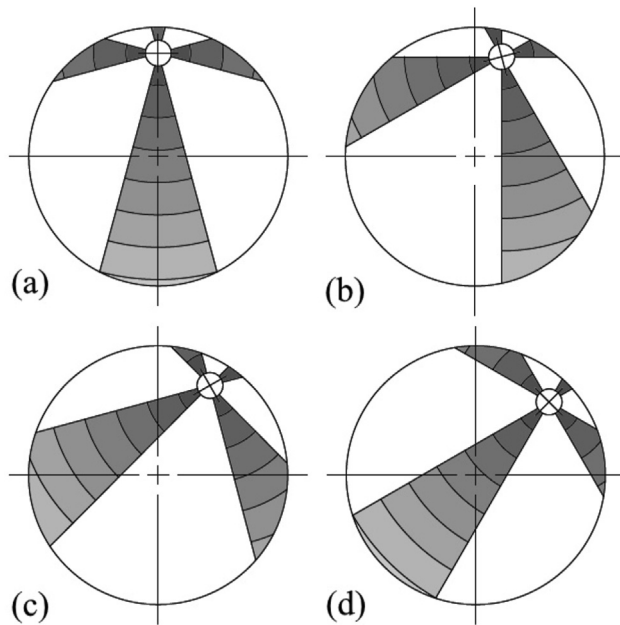


Fig. 12 – Directionality of ultrasonic excitation of the ceramic sonotrode in translation: (a) initial position; (b) 1/24; (c) 1/12; and (d) 1/8 of a cycle.

degassed. According to Atamenko et al. [16], for the ultrasonic melt treatment to occur, the amplitude of the sonotrode must be able to cavitation. In fact, Fig. 11 proves that the low amplitude of the ceramic sonotrode can generate cavitation and validates the discussion based on the PIV results of Figs. 5–7.

Considering the limitations of static Al melt US treatment, the synchronized kinematic translation system (Fig. 1 (b) and 4) was specially designed to maximize the distribution of acoustic power in the melt, taking into account the role of sonotrode orientation on the scattering of cavitation. As shown in Fig. 12, given the directionality of the ultrasonic sonotrode detailed in Fig. 5, the proposed synchronized kinematic translation is able to distribute the acoustic power in

the whole melt in 1/8 of a rotation cycle. Thus, by each kinematic cycle of the sonotrode, the whole melt volume has at least eight sweeping routines.

This allows that cavitation is efficiently nucleated and distributed in the entire volume of the Al melt. As shown in Fig. 13, the synchronized translation movement allows a continuous transition of the volume that is being degassed by the ultrasonic sonotrode. This is evidenced in the transition of the eigenfrequency harmonics that are captured by Cavitometer 1 (i.e. 0°) in the initial position of the sonotrode (Fig. 13 (a)), that are later captured by Cavitometer 2 (i.e. 45°) when the sonotrode is rotated 1/8 (Fig. 13 (b)) of a synchronized translation cycle. Moreover, the results attest the efficiency of the new approach on the cavitation distribution in higher melt volumes as the system is rotated, which is beneficial for an efficient removal of Hydrogen.

4. Conclusions

This study proposes a new approach to enhance the efficiency of ultrasonic melt degassing processes by designing a system that imposes a synchronized translation to ceramic sonotrodes. Considering that ceramic sonotrodes have been recently shown to work under complex eigenmodes, PIV tests in water reveal that this implies a strong directionality and higher streaming velocities occur in the directions in the excitation and perpendicular directions (i.e. 0° and 90°). This affects the cavitation distribution in the overall volume of the melt. Indeed, cavitometry tests show that synchronized kinematic translation may be used to assure the most effective sonotrode angle is always facing the center of the crucible.

Results on degassing highlight that the ultrasonic approaches are more efficient than the classic Argon inflation method ($H_{\min} = 0.22 \text{ ml}/100g_{\text{Al}}$; $\delta^*/\delta_0 = 98.0 \pm 1.5\%$) as they reach lower dissolved gas thresholds with higher degassing rates. The ultrasonic approach with synchronized kinematic translation is also shown to reach a lower dissolved gas threshold and higher specific densities ($H_{\min} = 0.13 \text{ ml}/100g_{\text{Al}}$; $\delta^*/\delta_0 = 99.6 \pm 0.3\%$) than the static sonotrode ($H_{\min} = 0.18 \text{ ml}/100g_{\text{Al}}$; $\delta^*/\delta_0 = 99.1 \pm 0.2\%$) approach. This evidences that,

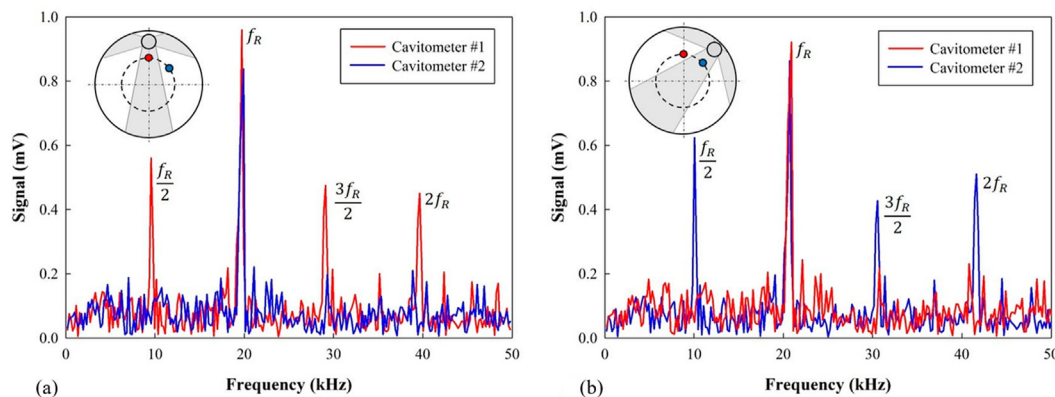


Fig. 13 – Cavitation in the crucible using the synchronized kinematic translation ultrasound melt treatment approach: (a) initial position; and (b) 1/8 cycle.

indeed, synchronized kinematic translation can distribute the generated cavitation more efficiently. This hypothesis is further supported by increased grain refinement relative to cast samples from the static ultrasound melt treatment approach. Both degassing and grain refinement in the cast samples with synchronized kinematic translation prove the suggested hypothesis result by displaying higher mechanical properties ($\sigma_y = 206 \pm 10$ MPa and $\sigma_{UTS} = 256 \pm 8$ MPa), relatively to the static ultrasound ($\sigma_y = 198 \pm 8$ MPa and $\sigma_{UTS} = 235 \pm 7$ MPa) and Argon inflation ($\sigma_y = 187 \pm 14$ MPa and $\sigma_{UTS} = 213 \pm 12$ MPa) approaches.

Synchronized kinematic translation in Al melt degassing processes with ceramic sonotrodes is proposed as an auxiliary approach that may allow an environmentally friendly (i.e. with a reduction or even no additives or use of consumables) and more efficient (i.e. quicker and lower degassing threshold) degassing in industrial scale light-alloy foundries.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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