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The combined effect of melt stirring and ultrasonic agitation on the degassing efficiency of $AlSi_9Cu_3$ alloy

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ABSTRACT

The combined effect of high intensity ultrasound and melt stirring on the degassing of $AlSi_9Cu_3$ using simultaneously the novel MMM (Multi-frequency Multimode Modulated) ultrasonic technology to promote cavitation, and low frequency mechanical vibration to induce melt stirring, was studied. On a first stage single low frequency mechanical vibration experiments were carried out in water in order to visualize and characterize its individual effect on the liquid dynamics. On a second stage ultrasonic vibration combined with different mechanical vibration frequencies, melt temperatures and processing times were tested in liquid $AlSi_9Cu_3$ alloy and their influence on the degassing efficiency was evaluated and compared with the results of the single MMM ultrasonic degassing technique. Fixed ultrasonic parameters (frequency and electric power) were used, according to the best results obtained in former experimental works developed by the authors. For the experimental conditions used in this research, it was found that melt stirring significantly improves degassing efficiency, and such improvement depends on the metal temperature and the mechanical vibration frequency. The experimental results suggest that combining melt agitation and ultrasonic vibration it is possible to achieve almost the aluminum alloy theoretical density without increasing the processing time.

1. Introduction

One of the most efficient, fast and environmentally friendly degassing method of Al alloys is based on the supply of ultrasonic energy to the molten metal in order to induce cavitation [1–3]. When a liquid metal is submitted to high intensity ultrasonic vibrations, the alternating pressure above the cavitation threshold creates numerous cavities in the liquid metal [4] which intensifies mass transfer processes and accelerates the diffusion of hydrogen from the melt to the developed bubbles. As acoustic cavitation progresses with time, adjacent bubbles touch and coalesce, growing to a size sufficient to allow them to rise up through the liquid, against gravity, until they reach the surface [4].

During the last years some of the authors developed an improved ultrasonic degassing apparatus (MMM — Multi-frequency Multimode Modulated technology) characterized by synchronously exciting many vibrating modes through the coupled harmonics and sub harmonics in solids and liquid containers to produce high intensity multimode vibrations that are uniform and repeatable [2,5] which avoid the creation of stationary and standing waves, so that the whole vibrating system is fully agitated, improving the degassing process.

However, ultrasound loses its oscillation energy and sound intensity along the path in a melt. If this loss is significant the intensity rapidly falls to the cavitation threshold and cavitation ceases, decreasing the degassing effect [4,6]. The displacement and the intensity of a plane ultrasonic wave decreases exponentially with the propagation path x, according to expressions (1) and (2) [4]:

$$A = A_0 e^{-\alpha x} \tag{1}$$

$$I = I_0 e^{-\alpha x} \tag{2}$$

where A is the displacement, I the intensity and α is the sound absorption, or attenuation, factor. Among other factors the absorption of ultrasound strongly depends on the viscosity of the melt, thus on the metal temperature, and its thermal conductivity.

Ultrasonic degassing performed so far has been running in a stationary volume of metal [2,3,7]. As a consequence of attenuation cavitation decreases gradually as the distance to the radiator increases, and cavitation only develops on a limited volume of molten metal close to the radiator. To attenuate this effect a modification to the original ultrasonic apparatus was made, in order to simultaneously induce a gentle stirring motion in the melt which would increase the volume of the metal developing cavitation.

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This paper presents the experimental study developed to evaluate the capability of the combined/simultaneous effect of melt stirring and ultrasonic agitation on the degassing efficiency of $AlSi_9Cu_3$ alloy over the single ultrasonic degassing technique.

2. Experimental procedure

The main components of the new version of the MMM ultrasonic system used in this research consist of a high power ultrasonic converter, an acoustic wave-guide and radiator, a low frequency mechanical vibrator coupled to the radiator by a helicoids interface, and a sweeping-frequency, adaptively modulated waveform generated by an MMM ultrasonic power supply (Fig. 1).

The equipment is fully controlled through Windows compatible software developed by MPI. Optimal ultrasonic parameters (sweeping and fswm = frequency shift with modulation) for the selected resonant frequency and electric power are adjusted in order to produce the highest acoustic amplitude and the largest frequency spectrum in the metal, which is monitored with a specifically implemented feedback loop.

The effect of the helicoids interface on the melt dynamics was evaluated in water, using a translucent container, since the water viscosity is similar to that of the molten aluminum at 700 °C [4]. Water is considered a suitable media to simulate liquid aluminum alloys by several researchers, either for modeling the ultrasonic degassing mechanism [8], to study the combined effect of gas purging and ultrasonic degassing [9] or to study/understand the cavitation effect and ultrasonic parameters in degassing [4].

For that purpose, the movement of the radiator for various vibration frequencies was measured by a high speed digital Photron, FastCam APX RS video camera capable of 10,000 fps at 1 Mpixel. Appropriate illumination is required and two high intensity beams were strategically placed in the vicinity of the viewing area. The video sequences were recorded at 1000 fps and a subsequent image analysis TEMA Motion software enabled the determination of the motion as a function of time. A mark was placed on the radiator surface and a scale was in view in order to calibrate the frames. From the position time series, the velocity and acceleration can be derived.

The specimen vibrations induce an oscillatory motion of the surrounding fluid. The radiator was placed in a circular vessel, 170 mm in diameter, filled with water. In order to reduce optical distortion, this was placed inside a square vessel filled with water. This way the mismatch of refractive indexes at the curved interface is reduced. The velocity field was measured by a two component DANTEC Laser Doppler Anemometry (LDA), with a spatial resolution of approximately 1 mm. The Doppler signals are processed in the frequency domain by Burst Spectrum Analyzers. 20 µm polystyrene tracer particles are used as a diffracting medium for the laser beams. For each position in the fluid, the mean velocity is statistically determined from 3000 samples. In this way, the velocity profile in the vicinity of the radiator is determined.

4 kg melting stocks of $AlSi_9Cu_3$ with the composition presented in Table 1 were melted in a resistance furnace equipped with a 170 mm diameter and 180 mm height SiC crucible. No significant chemical composition changes were detected after melting and degassing for 5 min, for every processing condition. Melt temperature was controlled within an accuracy of ±10 °C. Degassing was carried at 650 and 700 °C for 1, 3 and 5 min, using 19.8 kHz ultrasonic frequency, 750 W electric power and 15, 20 and 30 Hz mechanical vibration frequencies, using a 60 mm diameter radiator made of a titanium-based material. Results evaluation was based in the measurement of

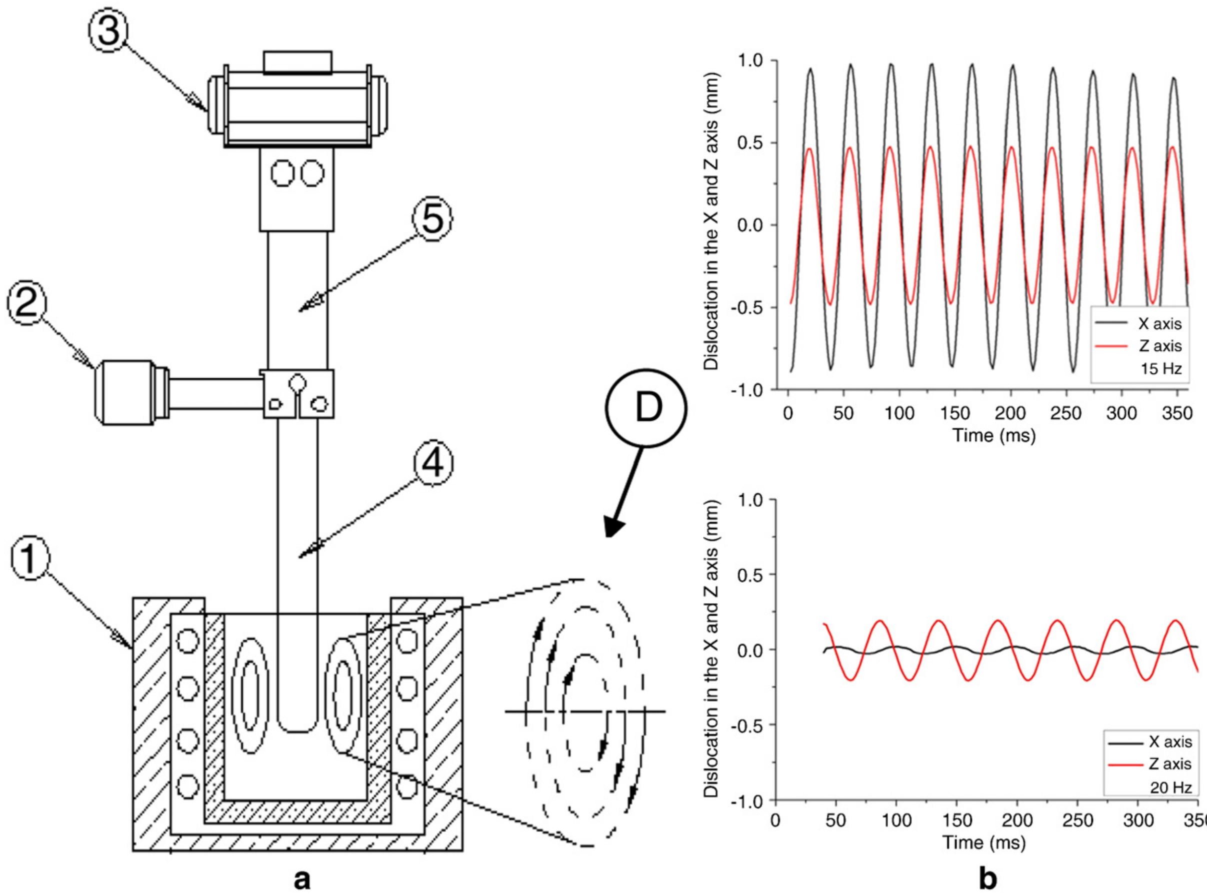

Fig. 1. a) Degassing apparatus including 1. furnace; 2. ultrasonic transducer; 3. low frequency mechanical vibrator; 4. radiator; 5. helicoids interface. b) Dislocation of the ultrasonic radiator under different mechanical vibration frequencies.

Table 1
Initial chemical composition of $AlSi_9Cu_3$ alloy obtained by optical emission spectrometry.

Element	Al	Cu	Fe	Mg	Mn	Ni	Si	Ti	Zn
wt.%	Bal.	2.93	0.7	0.24	0.26	0.06	8.3	0.03	0.4

sample density, which is directly related to the sample hydrogen content. The RPT test and the apparent density measurement method were used to evaluate the sample density [1,10]. Each density result is the average of 5 RPT samples taken for each processing condition. Degassing efficiency *h* was calculated from Eq. (3), where *D* is the theoretical alloy density (2.74 kg dm^{-3}), and *Di* and *Df* are the initial and final alloy densities, respectively.

$$\eta = \frac{Df - Di}{D - Di} \times 100. \quad (3)$$

3. Results and discussion

From the experiments conducted in water it was concluded that the low frequency vibrator promotes a helicoids motion of the ultrasonic radiator (Fig. 1b) that, in turn, induces an oscillatory motion in the water. The trajectory of the polystyrene tracer particles used as a diffracting medium for the laser beams followed an up and down loop movement revealing that the liquid near the container walls is forced to pass close to the radiator according to the motion profile and direction presented in Fig. 1-detail D.

The amplitude of the radiator dislocation in both *z* and *x* axes strongly depends on the mechanical vibrator frequency. Amplitudes close to 2 mm and 1 mm in *x* and *z* axes, respectively, were registered for 15 Hz frequency, and 0.1 and 0.4 mm, respectively, for frequencies in the range from 20 to 30 Hz (Fig. 1b). This resulted in a more intense liquid motion/stirring for 15 Hz frequency, which was easily visualized and confirmed by the higher dislocation velocity of the polystyrene particles in suspension along the loop referred above. Nevertheless, the effect of low frequency vibration in the fluid dynamics under these experimental conditions is not fully understood yet, namely the reason why an inversion in the relative amplitudes in *z* and *x* components occurs when frequency increases from 15 to 30 Hz. More experimental work is being developed in this particular field to understand the dynamical behavior of this particular vibration system and to characterize its capability to degas aluminum melts, and to understand the degassing mechanisms that are associated.

In ultrasonic degassing cavitation bubbles form mainly near the ultrasonic radiator due to the attenuation phenomena referred in Section 1, and are transported to the melt surface by acoustic streaming taking with them the dissolved gases (mainly hydrogen) which escape from the melt [4]. Nevertheless not every cavitation bubbles reach the surface since part of them are transported by acoustic streaming to the bulk melt and often collapse making the gases inside them to dissolve again in the molten alloy [4,9]. This mechanism tends to slow down the ultrasonic degassing process and may even limit the maximum alloy density achieved. According to the results of the experiments carried out in water, a similar motion profile induced in molten aluminum will help to overtake such drawbacks, since the liquid metal far from the radiator is forced to pass close to it, entering in a fully developed cavitation regime, which will improve degassing.

3.1. Effect of mechanical vibration frequency and processing time on degassing improvement

Fig. 2 shows the effect of vibration frequency to promote melt stirring on the sample density and degassing efficiency, for different processing times at 700 °C, using simultaneously 19.8 kHz ultrasonic frequency on the acoustic radiator.

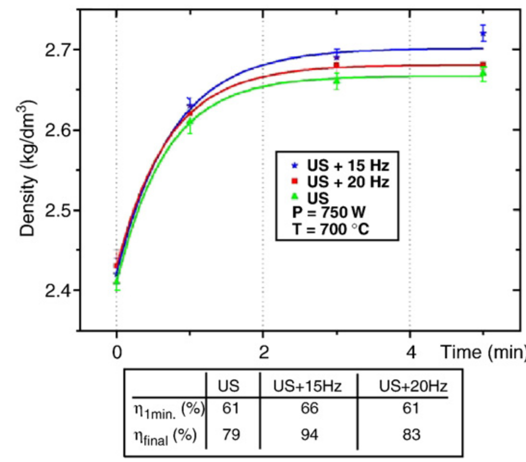

Fig. 2. Density of the RPT samples and degassing efficiency of the $AlSi_9Cu_3$ alloy as a function of mechanical vibration frequency and processing time, for the 700 °C melt temperature.

The maximum alloy density (2.72 kg dm^{-3}) is 0.05 kg dm^{-3} higher than that obtained by USD and was achieved after 5 min degassing, using 15 Hz for melt stirring. That value is very close to the theoretical alloy density indicated by the alloy supplier (2.74 kg dm^{-3}), and represents a degassing efficiency of 94%. For 20 Hz frequency, the maximum alloy density was 2.67 kg dm^{-3} which represents 83% degassing efficiency. In both cases, an improvement over single ultrasonic degassing (USD) is clear although much more significant for 15 Hz vibration frequency (Fig. 2). The difference to USD becomes more important as the processing time increases and the dissolved hydrogen content decreases. In single USD the approach of remaining H atoms to form H_2 gas molecules or its approach to cavitation bubbles is very difficult, because they are just a few and the distance between them is very high. However, the particular liquid motion profile induced by the mechanical vibrator promotes its approach to the ultrasonic radiator making it easier for its diffusion into the cavitation bubbles and its escape to the melt surface. When degassing starts this effect is not so notorious because the quantity of dissolved hydrogen atoms is much higher and distances between them and the cavitation bubbles are much smaller, making it easier for the diffusion process, thus degassing.

It is also clear from Fig. 2 that the kinetics of degassing is not changed by combining simultaneously ultrasonic and low frequency vibration, when compared with single USD [2,3,10]. As referred above

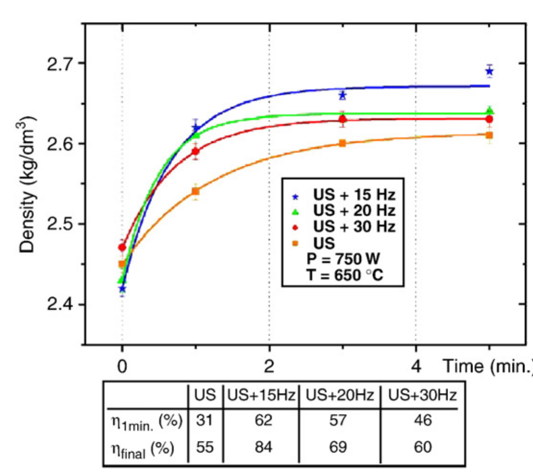

Fig. 3. Density of RPT samples and degassing efficiency of the $AlSi_9Cu_3$ alloy as a function of mechanical vibration frequency and processing time, for the 650 °C melt temperature.

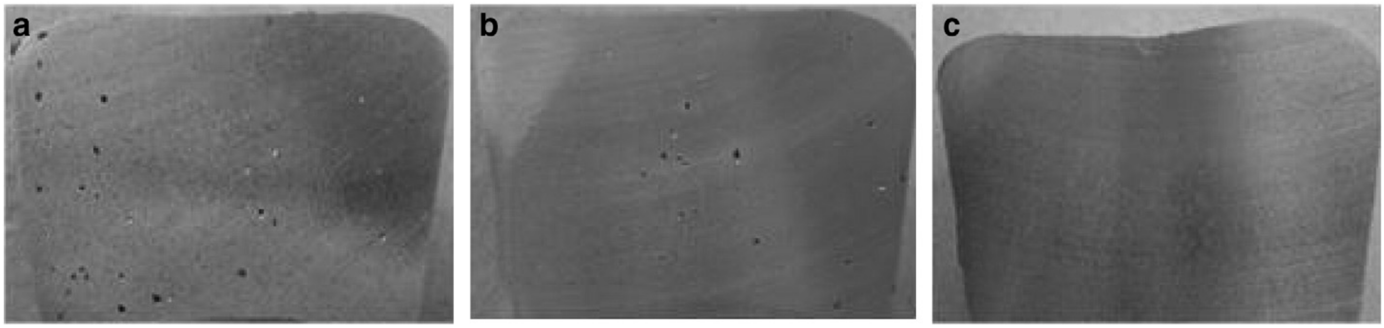

Fig. 4. Sections of the RPT samples after 3 min degassing using a) single US degassing; b) US degassing combined with 30 Hz mechanical vibration; c) US degassing combined with 15 Hz mechanical vibration.

the improvement in the degassing efficiency is due to the motion of the liquid metal that forces a greater volume of liquid to pass at distances from the acoustic radiator where cavitation develops, making it easier for hydrogen removal. Best results achieved for 15 Hz mechanical vibration deal with the higher dislocation amplitude of the acoustic radiator when compared with the 20 Hz vibration frequencies (Fig. 1b) that promoted more intense liquid motion and faster loop cycles.

3.2. Effect of the melt temperature on degassing improvement

The improvement on the degassing efficiency using the new combined technique over the traditional USD was much more effective for temperatures lower than 700 °C (compare Figs. 2 and 3), however maximum densities remained lower for 650 °C. At this temperature the maximum alloy density using the 15 Hz mechanical vibration frequency to promote melt stirring was 2.68 kg dm^{-3}, corresponding to 84% degassing efficiency, and decreased to approximately 2.63 kg dm^{-3} for 20 and 30 Hz (69 and 60% efficiency, respectively). This behavior is similar to that registered for the 700 °C melt temperature, since liquid motion decreases and loop movements become slower as the mechanical frequency vibration increases. When compared with the single US degassing experiments, melt stirring increased the degassing rate for every mechanical frequency vibration, since the degassing time to achieve the density steady-state plateau decreased from 5 min to around 2 min, for 650 °C melt temperature (Fig. 3). This is particularly evident by analyzing the porosity level of the RPT samples after 3 min degassing for single US degassing and using 15 and 30 HZ mechanical vibrations (Fig. 4).

For 700 °C, this effect is not so evident, and benefits mainly deal with the maximum alloy density achieved (Fig. 2).

At low temperatures three factors impair the capability of the USD process: a) as temperature decreases the acoustic wave attenuation factor strongly increases; b) the mobility of hydrogen atoms in the liquid metals decreases, slowing down the diffusion of hydrogen from the liquid to the cavitation bubbles; c) higher melt viscosity makes more difficult the pulsation of cavitation bubbles, their coagulation and floating to the surface [4,6]. The first two drawbacks can be overtaken by stirring the melt, as melt agitation increases the volume of metal where cavitation develops for the same reasons explained in Section 3.1, thus increasing hydrogen removal, and the low mobility of hydrogen atoms is compensated by liquid motion.

Nevertheless, the alloy density steady-state plateau is lower for lower degassing temperatures because below 700 °C the pulsation and development of cavitation bubbles are more difficult [4,6], and melt stirring cannot fully compensate such drawback. This is the reason why even using the combined US agitation/melt stirring the best results concerning to the final alloy density correspond to the highest processing temperatures.

4. Conclusions

- Melt stirring is an effective way to improve ultrasonic degassing of aluminum alloys, increasing both the alloy density and the degassing efficiency;
- For fixed ultrasonic parameters, the degassing efficiency and the maximum alloy density depend on the melt temperature and the frequency of the mechanical device used to promote melt stirring;
- For the ultrasonic parameters and setup used in this research, maximum efficiency (94%) and alloy density (2.72 kg dm^{-3}) were achieved for 700 °C and 15 Hz vibration frequency, decreasing for higher frequencies and lower temperatures.
- Although the results of water experiments should not be extrapolated with precision to aluminum melts, they were a good indication to anticipate the effect of low frequency mechanical vibration on the improvement of US degassing, giving an idea of the melt dynamics inside the melting crucible.

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