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Analysis of acoustic emissions from gas atomisation

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Abstract

It is well known that during close-coupled gas atomization introduction of the melt into the gas stream affects the emitted noise. However, there has been virtually no study of this 'acoustic signature'. In this paper we present a quantitative comparison of this acoustic signature for an atomizer under gas-only and gas + melt flow. We find that upon introduction of the melt there is strong absorption of frequencies in the 1-8 kHz range. These frequencies are characteristic of the resonance of droplets with 150-600 μm diameters and may be indicative of the dynamics of the initial breakup of melt ligaments. Moreover, during atomisation we find that there are considerable low frequency (< 30 Hz) fluctuations in the intensity of the acoustic emissions. We show this may be related to atomizer pulsation, the quasi-periodic low frequency variation in the melt volume instantaneously at the atomizer tip.

1. Introduction

Close-Coupled Gas Atomization (CCGA) is the technique of choice for the commercial production of fine (5-50 μm), highly spherical, metal powders such as might be utilised for Metal Injection Moulding (MIM) and Additive Layer Manufacturing (ALM). In principle CCGA is straightforward, high pressure gas jets impinging upon a molten metal stream are used to disrupt the stream, breaking it into a spray of fine droplets that then solidify in flight. However, the complex interaction between the high velocity gas and the metal results in a turbulent, and often chaotic, flow with the result being that the details of the process are far from well understood.

One of the most common manifestations of this complex interaction between the gas jets and the melt stream is atomizer pulsation. Commonly seen as a flickering of the luminosity of the atomisation spray cone, this is a short period variation in the amount of metal being instantaneously delivered to the atomisation tip[1]. During atomization, liquid metal is delivered down the central bore of the atomization nozzle, wherein it wets the nozzle tip and is stripped off the circumferential edge of the nozzle by the gas. The melt flow rate depends upon the pressure at the nozzle outlet, which in turn depends upon the dynamics of the gas flow. The application of high speed video analysis has been one of the key techniques in characterising and understanding the pulsation phenomenon[2, 3]. Through such analysis a significant scientific literature has built up attributing these fluctuations to the transition between open- and closed-wake conditions as the melt flow alternately disrupts, and is disrupted by, the Mach disk formed by the recompression shock in the supersonic gas flow[1, 2]. The formation of the Mach disk is in turn sensitive to the atomizing gas pressure[4], the design of the gas delivery manifold[5] and both the external[1] and internal[6] geometry of the melt delivery nozzle. It is postulated that this alternation between open- and closed-wake conditions leads to pressure fluctuations at the atomization nozzle tip which drive the observed pulsation, although this remains controversial, with some authors[5] arguing that wake-closure is of no real consequence during two-fluid atomization. However, recently a more complex pulsation behaviour has been uncovered[7]. At low pressure, where the atomizer would be expected to only be in the open-wake condition, the temporal distribution of melt volume instantaneously at the atomizer tip follows a log-normal distribution. Conversely, at high pressure the instantaneous melt flow-rate follows two superimposed log-normal distributions, one with a high flow-rate and low (geometric) standard deviation, the second with a lower flow-rate but higher standard deviation. In the high pressure case it is postulated that high-flow rate is associate with the atomizer being in the open-wake condition while the low flow-rate condition is associate with the atomizer switching to the closed-wake condition, with the system pulsing between the two states[7].

From a production point of view melt pulsation is likely to be a significant problem due to the consequent variation in the instantaneous gas-to-metal ratio, G. In [3], high speed video analysis was used to estimate the instantaneous melt flow-rate, from which the value of G was determined assuming uniform gas flow. This was found to vary between 1.26 (kg gas/kg metal) to 15.16 over a filming interval of < 4 s. This compares with a time averaged value of G, measured from the gas and metal consumption rates, of 2.84. The typical frequency of the variation was < 20 Hz. As far as we are aware, no studies exist relating the instantaneous gas-to-metal ratio to the particle size produced. However, extensive data correlating median as-solidified particle size to the average gas-to-metal ratio[8, 9] would suggest that high G is likely to correlate with small particles size and conversely low G with larger particle size. Consequently, significant short-period variation in G is likely to lead to substantial spread in the particle size distribution.

However, despite the advances in the understanding of the gas atomization process that high-speed video analysis has helped to bring about, there are very significant limitations as to its use. This

is particularly the case if we wish to do this in a production, as opposed to purely research, environment. These may be listed as follows:

1) The high cost of the equipment means that very substantial capital investment is required,
2) Most commercial gas atomization systems have very limited viewing ports and the positioning of cameras can be difficult and intrusive upon plant operation, there is also a risk of damaging the high cost optics,
3) Very careful positioning and alignment of the optics is required in order to obtain good results,
4) The application of such techniques is limited to high melting point metals wherein the melt stream is visible via its own radiant light,
5) The size of the data stream is very large and consequently real time processing of the data is not feasible.

For these reasons, in this paper we present a preliminary investigation of an alternative technology which has the potential to yield the same (or richer) data about the performance of gas atomizers but which is low cost, less intrusive and much more robust, both in terms of the care required in setting up the equipment and its own resilience to damage. Experience with commercial gas atomizers is that they are noisy (typically 100-110 dB at 1 m) and that the sound level is loudest in gas-only flow, subsequently dropping (typically by 10-14 dB) on introduction of the melt. Moreover, there is also a change in the tone of the noise produced whereby an experienced operator can often tell when a system is operating optimally from the noise it produces. Both phenomena are thought to arise due to the absorption of acoustic energy by the melt, with individual droplets selectively absorbing frequencies close to their fundamental mode of vibration, which is given by Yule & Dunkley[10] as

$$\omega = \frac{4}{\pi}\sqrt{\frac{\sigma}{\rho_L D^3}} \tag{1}$$

where σ is the surface tension of the melt, ρ_L the density of the melt and D is the droplet diameter. Indeed, this selective absorption of acoustic energy is used in both ultrasonic atomization and in the design of certain CCGA gas manifolds which include resonant cavities to promote frequencies corresponding to a desired particle size. However, the proposition here is that this selective absorption of acoustic energy can be used to develop a relatively simple system to characterise atomizer performance by analysis of its acoustic signature, essentially automating and formalising the trained ear of an experienced operator. In contrast to high speed imaging, acoustic recording is inexpensive and can be setup at a distance of ~ 1 m from the atomizer, without the need for direct line-of-sight of the melt plume. Moreover, the equipment is much more robust than precision optics, needs no careful alignment and produces a data stream of a size that would make real-time processing feasible. The acoustic monitoring of industrial plant is already commonplace, particularly as a means of providing early warning of the impending failure of mechanical systems[11].

2. Development of an Acoustic Analysis Methodology

To illustrate the principal we have made an audio recording during gas atomization at the Sheffield plant of Atomizing System Ltd. (ASL). The gas atomizer studied uses a gas delivery die of the annular slit type with the melt delivery nozzle having an included apex angle of 30º, a tip diameter of 9 mm and a central bore for the melt feed of 5 mm. During the trial recorded here the atomizer was operating with nitrogen gas at a gas inlet pressure of 2.4 MPa. The melt and gas flow rates were 0.25 kg s^{-1} and 0.35 kg s^{-1} respectively and a typical batch atomization takes ~15 minutes, wherein some 200 kg of metal is atomized. During the run recorded here the gas was pre-heated to an inlet temperature of 200 ºC, wherein the jet exit temperature upon ideal expansion will be -83 ºC.

The recording is 14:12 (mm:ss) in duration at a sampling rate of 44.1 kHz, giving ~ 37 M samples. The theoretical maximum frequency resolution at this sampling rate is 22.05 kHz. However, to avoid the introduction of artefacts when the sound being recorded contains frequencies higher than this, the recording apparatus was equipped with an anti-aliasing filter with a cut-off at 15 kHz. Figure 1 shows two short sequences of this recording at the start (Fig. 1a) and end (Fig. 1b) of the atomization process. Prior to the start of atomization there is some noise due to the induction heating system being used to melt the metal (i). The gas is introduced first leading to a sharp increase in the acoustic intensity (ii) followed, as expected, by a drop in intensity over the next 3 s or so as the metal is introduced (iii) and its flow attains steady-state (iv). In Fig. 1b we see the end of the steady-state period of melt flow (iv). As the melt is exhausted (v) the acoustic intensity increases reaching a maximum when the atomizer returns to gas-only flow (vi). Finally the noise level drops as the operator shuts off the gas supply (vii) with the final valve closure evident as a sharp spike in the intensity, followed by a lower intensity signal from the induction heater (viii) prior to this being shut down.

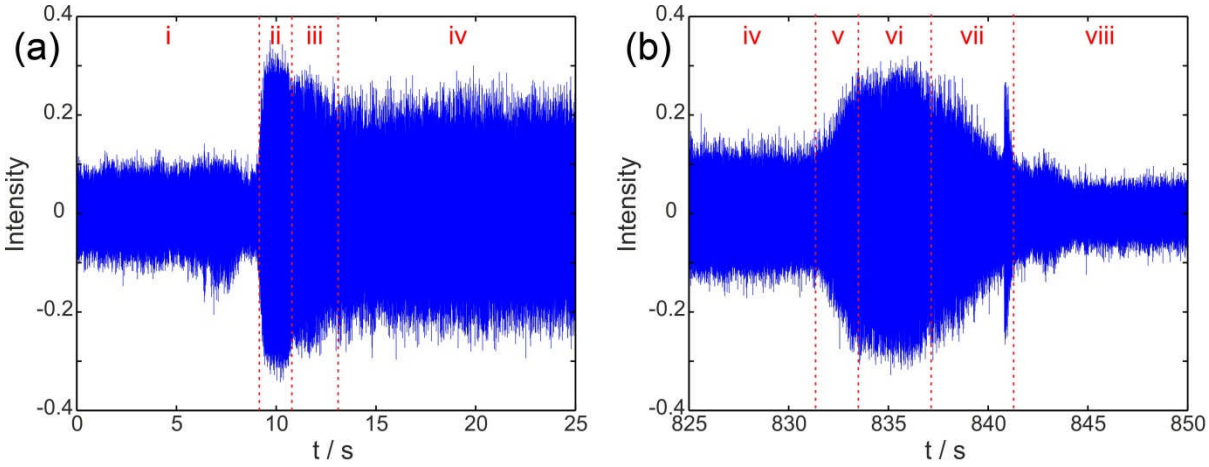

Figure 1. Two short sections of the waveform obtained from an audio recording of (a) the first 25 s and (b) the last 25 s of a gas atomization run. The regions identified are (i & viii) background noise from induction heating, (ii) gas-only noise prior to melt introduction, (iii) transient due to melt introduction, (iv) steady-state during atomization, (v) transient due to exhaustion of melt supply, (vi) gas-only noise following exhaustion of melt supply, (vii) transient during shut-off of gas supply.

We can see from Fig. 1 that the introduction of the melt does indeed significantly reduce the intensity of the sound produced by the atomizer. Moreover, by taking the Fourier transform of a sample of gas-only noise and comparing it with the Fourier transform of a sample of (gas + metal) noise we can demonstrate that this reduction does indeed appear to be due to the selective absorption of certain frequencies, as predicted by Equation (1). The sample of gas-only noise is taken from region (vi) in Figure 1b. As the recording was taken during a commercial atomization run the duration of gas-only flow was kept to a minimum and for this reason the sample is just 3 s. The sample of (gas + metal) noise is taken from the middle of the atomization run (region iv in Figure 1b) and, in order to maintain direct comparability, was also restricted to 3 s. The ratio of the (gas + metal) to gas-only noise is shown in Figure 2, which shows that upon introduction of the melt there is strong absorption of frequencies in the 1-8 kHz range, typically by around -7 dB relative to the signal for the gas-only noise. These frequencies are characteristic of the resonance of droplets with 150-600 μm diameters. However, two regions are observed where this uniform -7 dB absorption is not evident. At low frequency (< 400 Hz) the (gas + metal) noise is greater than that of the gas-only noise. These frequencies are too low to correspond to droplet breakup as described by Equation (1) and are probably an artefact. Perhaps of more interest is a sharp, ~ -10 dB, dip in the ratio of the signals around 4.8 kHz, indicating strong absorption of the sound by the metl around this frequency. Equation (1) predicts that such frequencies would correspond to a particle size around 200 μm diameter, which may be indicative of the dynamics of the initial breakup of melt ligaments.

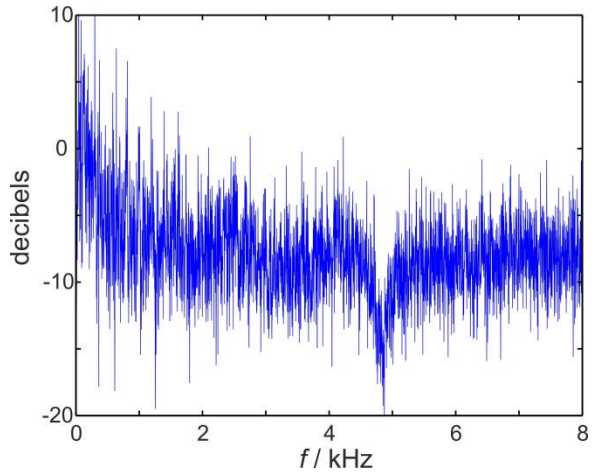

Figure 2. Ratio, as a function of frequency, of the (gas + metal) to gas-only noise.

It is a relatively small step to postulate that this behaviour is likely to be reflected in the instantaneous behaviour of the atomizer (i.e. that the atomizer is louder when there is less melt instantaneously at the atomization tip and quieter when more melt is present), wherein an amplitude

modulation of the noise produced by the atomizer would arise from which atomizer pulsation can be monitored. To assess any amplitude modulation of the acoustic signature over short (1-25 s) timescales we have applied standard signal processing techniques. The audio signal is first rectified (i.e. the negative half of the waveform is converted to positive) before a low-pass filter is applied which will recover the amplitude modulation without *a priori* knowledge of the frequency spectrum of the modulated wave. To study the acoustic response over longer timescales a simple moving RMS average has been applied.

In these trials an infinite impulse response (IIR) filter was used. IIR filters are one of two primary types of digital filters used in Digital Signal Processing applications (the other type being finite impulse response, FIR). Unlike FIR filters, IIR filters have feedback (a recursive part of a filter) and typically meet a given set of specifications with a much lower filter order than a corresponding FIR. For a recursive IIR filter the n^{th} component of the filter output signal, $y(n)$, is given in terms of the filter input signal, $x(n)$, $x(n\text{-}1)$, $x(n\text{-}2)$ …, by

$$y(n) = \frac{1}{a_0}\left[\sum_{i=0}^{M_f} b_i x(n-i) - \sum_{i=0}^{M_b} a_i x(n-i)\right] \tag{2}$$

where b_i are the feedforward filter coefficients and a_i are the feedback filter coefficients. Here the filter is of order M_f in the feedforward component and M_b in the feedback component.

The particular filter used here was designed such that frequencies ≤ 40 Hz pass through unattenuated (gain = 1, or 0 db). For frequencies > 40 Hz the attenuation rises smoothly to -80 dB at a frequency of 100 Hz. This required a three section filter of order 11 in both M_f and M_b. However, for those unfamiliar with digital signal processing these details may be ignored. The frequency transfer characteristics of the filter are shown in Figure 3 and in essence the process is to apply the filter shown in Figure 3 to a rectified version of the sound recording. Low frequencies pass through unattenuated, while higher frequencies are very effectively blocked (80 dB is a factor of 10^8 reduction).

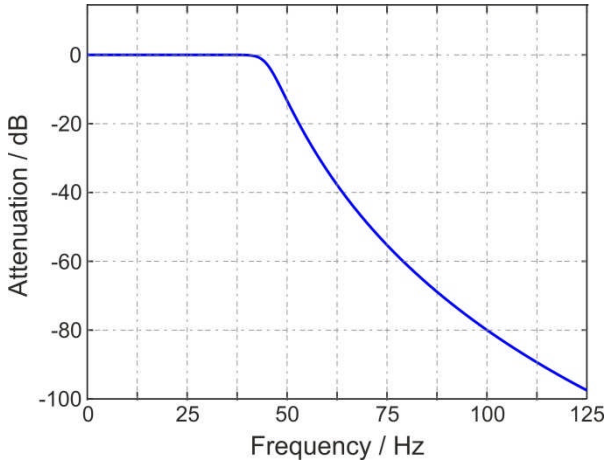

Figure 3. Frequency transfer characteristic of the IIR filter used in this work.

For long period analysis the moving average was calculated using a 2 s (88,200 sample) window which was advanced by 1 s (44,100 samples) at a time, giving a 50% overlap between adjacent averages. This is roughly equivalent to applying a filter with a 0.5 Hz pass band (c.f. 40 Hz pass band used above), allowing the broad characteristics of the whole recording to be assessed.

3. Results - Amplitude Modulation Analysis

Figure 4 shows a 4 s portion of the recording following signal processing with the IIR filter to recover any amplitude modulation in the acoustic signal. The nature of the variation is qualitatively similar to that obtained using high speed imaging to measure the volume of melt instantaneously at the tip of the melt delivery nozzle (compare for instance Figure 4 here with Figure 3b in Ref. [7]), with the caveat that here low acoustic intensity will imply high melt flow-rate.

However, to confirm the validity of the signal being recovered we have also tested the signal processing routine on samples of both uniform and Gaussian ‘white noise’. From [7] we have reason to believe that the melt flow-rate has a log-normal variation. As such, a log-normal variation in the recovered audio signal would tended to confirm that it was mirroring the melt flow-rate, particularly if an identical analysis applied to ‘white noise’ does not produce such a trend. To this end filter output from both the atomizer recording and the ‘white noise’ sample have been subject to statistical

analysis. In each case the time series data resulting from signal processing was converted to a cumulative frequency plot, wherein the temporal distribution could be analysed. Six 25 s sample recovered from the audio recording were analysed and in each case it was found that the intensity distribution could be approximated by a log-normal distribution, exactly as has been found to be the case with melt flow-rate data obtained from high speed imaging experiments[7]. The average skewness for the six samples was +0.18. In contrast the 'white noise' samples did not show this property, with the average skewness being -0.017 and +0.004 for the uniform and Gaussian samples respectively. Consequently, the 'white noise' samples could not be modelled as log-normal, appearing instead to be much closer to being normally distributed (as opposed to log-normally distributed). That the signal recovered from the audio recording of gas atomization displayed a property that we know might be expected in atomizer pulsation (a log-normal distribution of intensities) and that this was not replicated by 'white noise' samples passed through an identical processing routine, gives confidence that the signal does indeed carry useful diagnostic information relating to the atomization process.

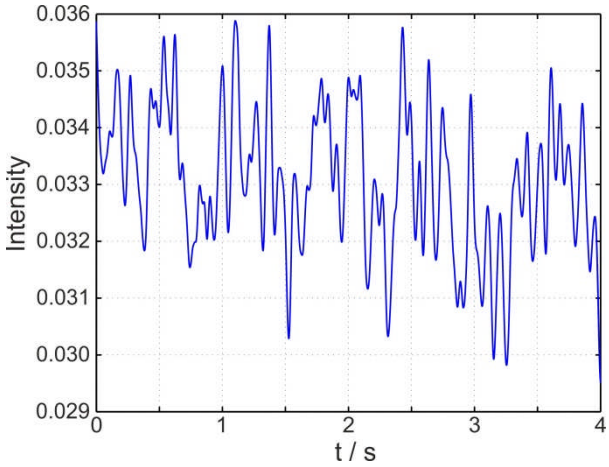

Figure 4. Result of applying amplitude de-modulation to a 4 s portion of the audio recording obtained during gas atomization (from region iv, gas + metal flow). Approximate 20% variation in the overall audio intensity of the signal is apparent during the 4s period shown.

Above we have demonstrated that acoustic recording could, in principle, be used to obtain the same type of data as has previously been obtained using high speed imaging. However, there also appears scope to obtain information that cannot be obtained using high speed imaging. One of the limitations of high speed imaging is the relatively short recording time available due to the very large data sets generated. In [3, 7] we reported data based on 3.64 s of video recording (65536 frames at 18000 fps) and of necessity we were unable to resolve features with a longer period than this. In contrast, calculation of an RMS moving average provides a simple and computationally inexpensive means of analysing an entire atomization run that may last many minutes.

Figure 5 presents the moving average data for the whole atomization run. Prior to applying the moving average, the initial and final 20 s of the recording were cropped so as not to influence the moving average with the gas-only transients at either end of the recording. A number of long period variations in the acoustic intensity are apparent. The most noticeable of these is that the average sound intensity drops consistently during the atomization run. This is manifest as first an abrupt drop in intensity around 50 s in to the run, followed by a drop in intensity of around 30% between 100 s and the end of the recording. The origin of this is unknown, but we speculate that it could be related to thermal loading of the system as the average system temperature rises during atomization due to the heat content of the liquid metal. Also apparent from Figure 5 is a pulsation behaviour with a period that drifts between 10 – 15 s and which is manifest as a superimposed oscillation on the signal. This behaviour, which is more pronounced during the second half of the atomization run, can also be detected if portions of the recording are run through the IIR digital filter, although this process is more computationally expensive and is limited to short samples. Again, the origin of this pulsation is unclear, although we think it unlikely that fluctuations in the gas flow-field, such as the open- to closed-wake transition normally cited as the origin of atomizer pulsation, could operate with such a long period. One possible explanation, although this is yet to be verified, is that metal is periodically solidifying on to the tip of the melt delivery nozzle and then being broken-off by the gas jet. Such accretions are visible on the melt nozzle following atomization and tend to build up on the initially flat tip of the melt nozzle, elongating it further into the gas stream and creating a pointed, rather than flat tip. It is well known that the aspiration pressure is a sensitive function of the melt nozzle geometry so it would therefore not be surprising for changes in the melt nozzle geometry to lead to fluctuations in the melt flow rate.

This would also explain why this particular long-period oscillation is more prominent during the latter stages of the atomization process, when such accretions are more prevalent.

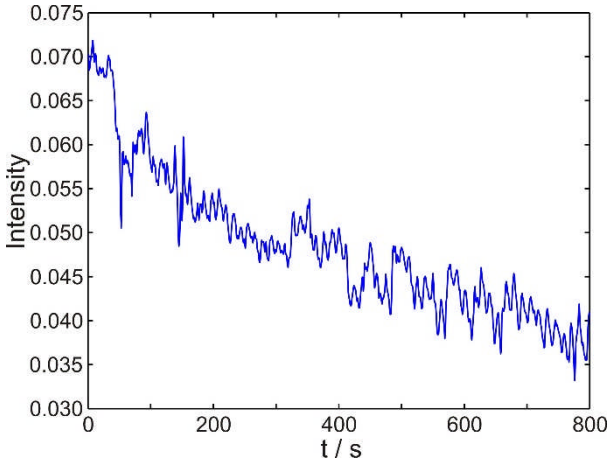

Figure 5. Average acoustic intensity during atomization showing a consistent decrease in intensity over time and a superimposed oscillation with a 10-15 s period.

4. Summary and Future Outlook

A preliminary analysis of an audio recording made during close-coupled gas atomization has revealed that such recordings could prove a valuable tool to study pulsation phenomena during atomization. Audio recording has the potential to allow such pulsation phenomena to be studied at much lower cost than current techniques, which generally involve filming the atomizer at high frame rates. Acoustic techniques are also much more robust and less intrusive on plant operation. However, a further and perhaps as yet unrecognised advantage, is that audio recording will allow the study of much longer period instabilities during atomizer operation. During this preliminary analysis two such were identified, including a quasi-periodic oscillation with period 10 – 15 s which increases as atomization proceeds.

However, it is also the case that the audio signal provides a less direct means of studying atomization than high speed video analysis. From a video analysis it is a relatively straightforward matter to estimate the volume of melt instantaneously at the atomizer tip. In contrast, in the audio signal, although evidence of atomizer pulsation is evident, it is not at all clear that a simple linear relationship between acoustic intensity and melt volume exists. Simultaneous video and audio recording will allow the pulsations in the audio recording to be calibrated against the same pulsations in the video data such that the relationship between the audio signal and melt flow may be elucidated.

Preliminary evidence also indicates that Fourier analysis of the audio signature could yield useful information about the size of droplets present, particularly in the primary atomization zone and with regard to ligament break-up. This analysis could be extended using short-time Fourier transformations to produce a time-resolved frequency analysis (spectrograms) to determine whether pulsations in the acoustic amplitude were correlated with changes in the frequency spectrum of the acoustic signature of the atomizer. Such analysis could yield information as to whether the dominant particle size being instantaneously produced was varying as a consequence of atomizer pulsation.

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