Advanced Materials Research Vols. 13-14 (2006) pp. 291-297
online at http://www.scientific.net

Application of acoustic emission for monitoring the HVOF thermal spraying process

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Keywords: Acoustic emission; Thermal spray; HVOF; Non-destructive testing; Monitoring

Abstract. This research aims to characterise and quantify the acoustic emission (AE) generated during the high velocity oxy-fuel (HVOF) thermal spraying process, recorded using piezoelectric AE sensors. The HVOF process is very complex involving high temperature turbulent flow through a nozzle with entrained particles, the projection of these particles, and their interaction with the target surface. Process parameters such as gun speed, oxy-fuel pressure and powder specification affect various characteristics of the coating, including thermal residual stresses; the lamellar microstructure and the topology and geometry of pores, all formed when the fused powder hits the surface, forming "splats". It is widely acknowledged in the thermal spray industry that existing quality control techniques and testing techniques need to be improved. New techniques which help to understand the effects of coating process parameters on the characteristics of the coating are therefore of value, and it was anticipated that recording the AE produced when the fused particles contact the surface would aid this understanding. As a first stage, we demonstrated here that AE associated with particle impact can, in fact, be discerned in the face of the considerable airborne and structure-borne noise.

In order to do this, a new test method using a masking sheet with slits of varying size was developed. Thermal spraying was carried out for a range of spray gun speeds and process parameters. The AE was measured using a broad band AE sensor positioned on the back of the sample as the spot was traversed across it. The results show that the amplitude and energy of the AE signals is related to the spray gun speed, powder used and the oxy-fuel pressure. Using a simple geometrical model for particle impact, the measured AE was found to vary with the energy and number of particles impacting on the sample in a predictable way.

Introduction

In this work, the relationship between measured Acoustic Emission (AE) parameters and Thermal Spray (TS) process parameters is investigated. AE detection during spraying of sprayed coatings is has an advantage over current conventional coating quality testing techniques such as indentation, bending and residual stress analysis, which are of a destructive nature and cannot be carried out during the process. There are no industrial on-line coating quality monitoring systems and quality control usually involves post-process acceptance sampling/testing of test coupons.

"Thermal spraying" is a generic term used for processes wherein the sprayed layer is built up by partially melting the powder material to be coated in a high temperature zone (a flame or plasma) and propelling the molten droplets onto the substrate in the form of splats (Pawlowski, 1995). Various process technologies exist (e.g., HVOF, Plasma Spray, Detonation Spray and Cold Spray) and all are used to produce thick-film coatings to combat surface degradation of engineering components by wear, corrosion and fatigue crack initiation. The kinetic energy of small particles has been found to dissipate within the substrate material in the form of elastic energy (Hutchings, 1977), and AE can, in principle, be used to characterize such strain energy because it is generated by rapid release of strain energy within a material. Part of the energy radiates from the source in the form of elastic waves which propagate over the material surface and can be detected using AE sensors. This can be relatively simply shown for single elastic impacts, but the situation is more complicated in spraying where the particles undergo significant plastic deformation, there are many, perhaps overlapping events and a number of secondary processes (such as the collapse of particle agglomerations and phase changes) going on (Fauchais et al., 2004). There has been some research undertaken to study thermal spray process other than HVOF such as arc spraying (Bohm et al., 1989) and atmospheric plasma spraying (Crostack et al., 1993, Lugscheider et al., 1999, Nishinoiri et al., 2003) using AE techniques. Interestingly, Bohm et al. (1989) found the energy of AE signal calculated using auto-correlation function proportional to kinetic energy of impacting particles. Crostack *et al.* (1993) and Lugscheider et al. (1999) developed a model which relates the particle velocity and diameter of powder particles with the amplitude of AE signals. Most recently Nishinoiri et al. (2003) used laser AE technique to study microfracturing, delamination and cooling process during spraying. AE parameters can be successfully correlated with HVOF spray process parameters and coating properties then it may be possible to use AE as a process control parameter to improve cohesive and adhesive strength, hardness, porosity and tribo-mechanical properties of thermal spray coatings using this technique. In continuous thermal spraying the AE signal is expected to be relatively constant in magnitude with no obvious bursts, due to the accumulative effect of many impacting particles. So, in order to study the fundamental processes, and to reduce the number of particle impacts per unit time, a pre-determined array of slits were placed between the spray gun and the substrate.

The overall objective of this study is to determine if the sources of AE generated during HVOF thermal spraying can be characterised in relation to final coating structure and to the spray process parameters such as gun transverse speed and gas pressure for a given powder-particle size and spraying distance.

Experimental Systems and Techniques

This experiment involved an HVOF (TAFA JP-5000, Monitor Coatings Ltd., UK) thermal spraying system using WC-10Co-4Cr powders (AMPERIT® 558.074) of size 45/15µm, an AE sensor, data acquisition system and an experimental rig for in-process AE monitoring as shown in Fig. 1. Here, a fixed set of process parameters for the HVOF spraying system were chosen: spray gun stand-off distance (15 inch), powder feed rate (80g/min.), oxygen flow rate (1950 standard cubic feet per hour, scfh), with nitrogen as the powder carrier gas, fed at the rate of 21 scfh. In addition, the following process parameters were varied during the experiments: spray gun lateral speed (250, 500, 750, 1000 mm/sec) with no cooling air nozzles, fuel flow rate (6 and 4.5 gallon/min, i.e. two levels of fuel pressure, P1 and P2), and the range of slit arrangements investigated was (A: 3mm×10mm, B: 2mm×10mm, C: 1mm×10mm, D: 0.5mm×10mm). The test was devised to observe whether or not a clear signal could be recorded while the substrate material is being coated, and whether this signal is distinguishable from that associated with the continuous background noise.

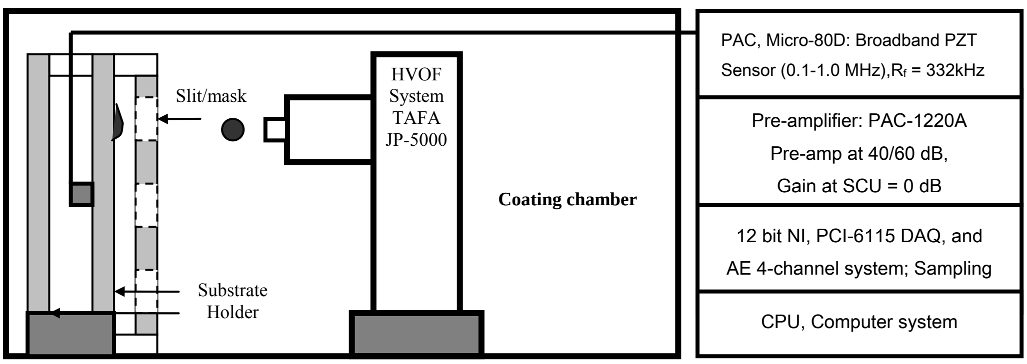

Fig. 1. Block diagram of the HVOF and AE experimental set-up with masking sheet

The masking sheet, coating substrate and holder were made of mild steel sheet of size 300mm×500mm×3mm thick and the mask had an array of varying sized slits cut into it using a Ferranti MF600 CO_2 laser CNC machine. Each row of the array consisted of a set of one particular size of slit, equally spaced with a 30mm edge-to-edge gap across the width of the mask (Fig. 2). The substrate and holder were both securely clamped to a stand, and an AE sensor was located in the middle of the grit-blasted substrate on the reverse side to that being sprayed, and held in place using a magnetic holder with silicon grease to eliminate air gaps. It was verified that no measurable AE was transmitted from the mask to the substrate using a simulated source (pencil lead break test).

Results and Discussion

AE Signal Characteristics. The AE signals were acquired from the sensors at full bandwidth so that spectral analysis could be carried out on the raw signal and also so that time domain characteristics could be examined up to the waveform resolution.

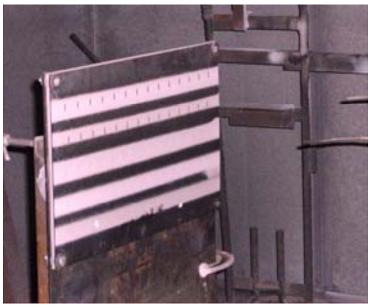

Fig. 2. Slit array

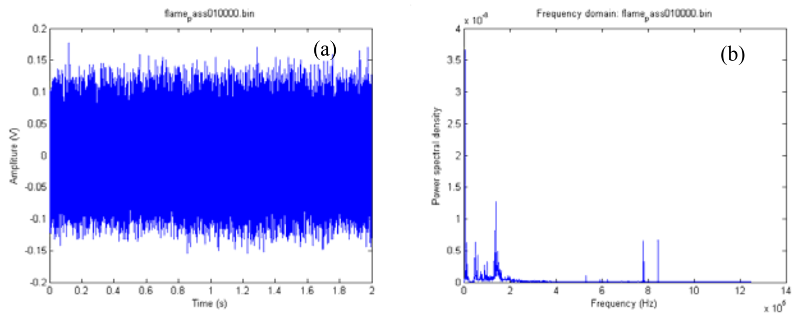

Fig. 3. AE signal (a) amplitude and (b) frequency, recorded during HVOF flame-only spraying onto substrate without powder (flame noise)

Only a few representative AE signals are discussed here simply to identify the type of information that can be obtained. To differentiate between the signals generated due to flame noise and powder particle impact, three reference conditions were used, those being (a) spraying with flame and powder particles directed behind the sample (background noise) (b) spraying with only flame onto the substrate (no powder) to examine the effect of flame noise, and (c) full spraying, i.e. spraying with powder and with flame onto the substrate. During flame and powder spraying behind the sample (i.e., background noise), the main frequency components are at around 5, 50, 100 and 140 kHz and the signal amplitude remains 0.15-0.2V which is similar to the result shown in Fig. 3 acquired during spraying onto the substrate without powder. A single powder particle splat on a grit-blasted surface due to perpendicular impact can be seen in Fig. 4.

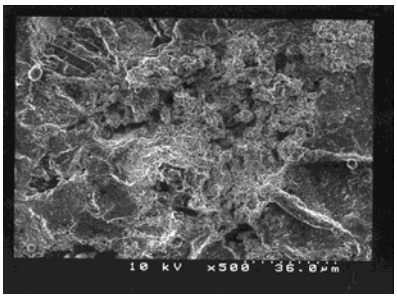

Fig. 4. Single WC-10Co-4Cr powder impact: splat located in valley on grit blasted surface, i.e. interlocking

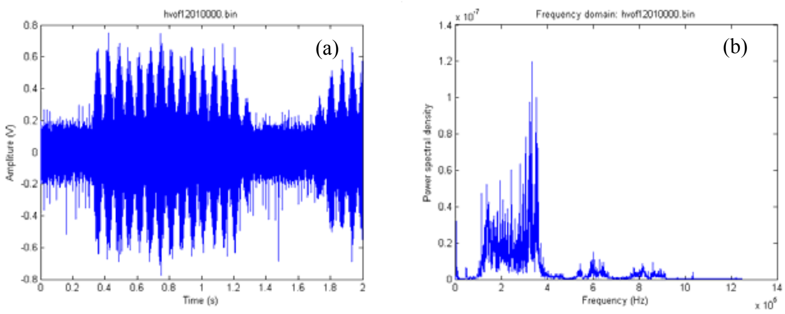

Fig. 5. AE signal (a) amplitude and (b) frequency spectrum, recorded during HVOF full spraying (both flame and powder) onto substrate through slit-A at 500 mm/sec, and pressure P1

As can be seen from Fig. 5 spraying directly onto the substrate through a slit gives rise to pulses of about 0.6-0.7V, giving a signal-to-noise-ratio: SNR of at least 3 at 0.2V background noise level, depending on the slit size. Also, the spectrum shows very different characteristics to the flame noise with a broader band and considerably more energy in the high frequency components. As expected, different AE signatures were detected when spraying through slits of different size, a representative AE signal for slit-A being shown in Fig. 5 for spraying at pressure P1. It is shown that every pulse in the AE signal corresponds to the position of a slit, there being 14 pulses per traverse of the specimen. Because the record length is 2 seconds (i.e. 2 layers at 500mm/sec gun speed), the second group of pulses is associated with the return of the gun on its subsequent traverse, the gap between the two groups being associated with the spray gun off-set distance of 150mm. On comparison with the AE associated with spraying across the same 14 slits at reduced pressure P2, it was found that the AE amplitude decreases by almost half if the pressure is reduced by 25%. There are also changes in the frequency spectrum where the power of the spectrum did reduce and for the two main frequency bands of interest, at around 100-200 kHz and 300-400 kHz (see Fig. 5), which means that the relative proportions in these two frequency bands change at reduced pressure.

Influence of Process Parameters and Multi-layer Spraying. Varying the gun transverse speed should alter the sprayed particle flux per unit area landing on the substrate, a factor which is known to affect the strength of the coating layer (Nishinoiri et al., 2003). In order to examine whether the expected change in flux per unit area is reflected in the signals scanned through the various configurations of slit, the event count, energy and event duration was calculated using a threshold of 0.2V (noise).

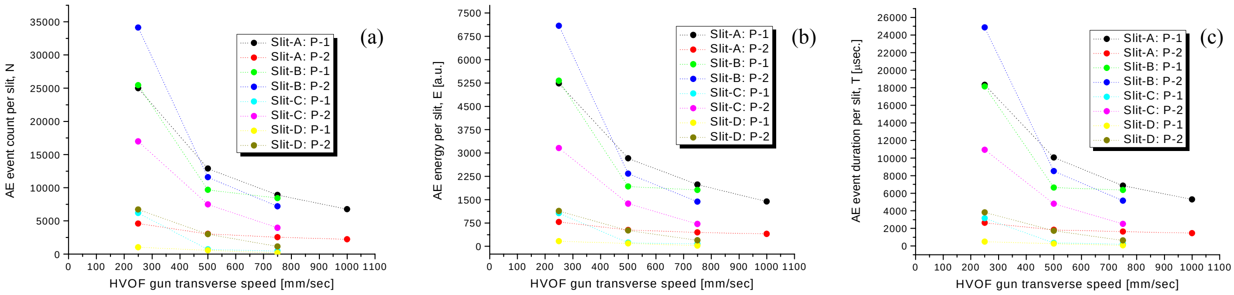

Fig. 6. Influence of HVOF gun speed on AE (a) event count (b) energy (c) event duration

As the gun speed increases the number of events decreases as shown in Fig. 6(a) indicating a relationship with number of particles. As the slit width reduces the number of events decreases. It was also observed that, when pressure is reduced, the number of AE events decreases for a given traverse speed, again as would be expected because the mean particle flux (average speed of particles) decreases with pressure. The trends in the AE energy level, shown in Fig. 6(b), calculated for each event above threshold level and adding the event energies up using $E = \int V_{abs}\, dt$ where V_{abs} is absolute voltage and dt is the event duration calculated above threshold level, are the same as for event count. The trends for AE event duration (i.e. total cumulative time above threshold per slit) as shown in Fig. 6(c), are again similar. The event duration through a single slit is inclusive of particle impact time (or loading time) and cooling time as the splat cooling rate for sprayed coating varies between 100-600K/µs depending on the splat flattening degree (Fauchais et al. 2004). So, an individual particle encounter is expected to generate AE during impact and during cooling, and an increased flux per unit area would not be expected to increase this duration. Therefore, the observed "events" are likely to be the result of several overlapping particles encounters and the changes in "event duration" can be identified with the number of overlapping encounters in the time window.

A preliminary test was carried out by spraying continuously at 200mm/sec gun speed on a flat mild-steel substrate for 5 layers and the AE energy distribution across the five layers (Fig. 7(a)). As can be seen, the AE energy within a layer goes through a maximum (circled in Fig. 7(a)) as the spray spot passes over the sensor position in the middle of the back of the sample. As well as this, there is a general increase in AE energy as the number of layers builds up which may be related to in-layer and inter-layer thermal mismatch producing micro-cracks as the coating builds-up. It is therefore possible that AE monitoring may, as well as providing information on the particle-surface encounter mechanism, also offer insight into the *in situ* fracture mechanism during spraying, which would, in turn add to its capacity for in-process quality assessment. Fig. 7(b) and Fig. 7(c) show representative AE records under continuous spraying, the former showing the noise and the latter demonstrating that the SNR is 3 at 0.2V background noise. It was also observed that, when the AE count or energy is normalised with respect to event duration time (N/Δt, E/Δt) for a given slit size, the AE 'power' is independent of gun speed but reduces with slit width and gas pressure.

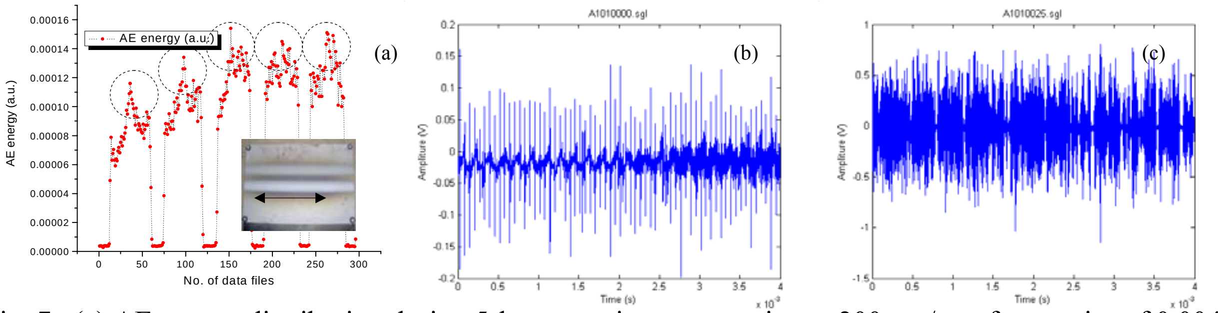

Fig. 7. (a) AE energy distribution during 5-layer continuous spraying at 200mm/sec, for a series of 0.004 sec record lengths; individual AE records during continuous HVOF spraying (b) gun missing substrate (noise), (c) gun on substrate, S/N ratio >3

In industrial practice, engineering components are thermally sprayed in a continuous multilayer mode, so the development of on-line monitoring will need to acknowledge the effect of very large numbers of particles, and will have to be done in conjunction with post-spraying tests to identify cohesive and adhesive strength, hardness and residual stress.

Development of Kinematic Model of Particle Impact. As seen above, the slit experiments have demonstrated that spray-substrate interaction generates measurable AE, although it is by no means certain that individual particle impacts will be observable either by the time- or amplitude-resolution of the method. It is therefore of interest to develop a model describing the approaching particle density, size and velocity distributions as an aid to analysing the data from slit and slit-free experiments. As a first stage in the process, a cross-section of the spray can be assumed to contain a constant density of particles of constant size, travelling at constant velocity and the total particle kinetic energy passing through a slit determined as a function of time, as shown in Fig. 8.

1. Area of full spray circle (at angle 2π) = πR^2; R is radius of spray spot; slit height $Z > 2R$
2. Effective Area spraying through the slit at any given 'θ' & 'δ' = Area ($BB'B_1'B_1$)
   The effective area ($BB'B'_1B_1B$) = [Area ($B'B_1'CB_1BDB'$)] – [Area ($B_1'CB_1D'B_1'$)]
   $= (1/2) . [R^2 \{2 (\theta-\delta) - (\sin 2\theta - \sin 2\delta)\}]$
   Angle $\angle BOB' = 2\theta$; Angle $\angle B_1OB' = 2\delta$
   And, $\theta(t) = \pi . (t/T_\theta) = [\pi . t . V_g/2R]$ and $0 < t < 2R/V_g$ & valid for slit width $0 < y < R$,
   $\theta = \pi$, when the spray edge (C') crosses the slit edge BB', continues until (C') crosses slit edge B_1B_1'
   $T_\theta = 2R/V_g$; Similarly $\delta(t) = \pi (t/T_\theta) - \pi (t_y/T_\theta)$; where $t_y = y/V_g$, V_g is speed of gun
   Or $\delta(t) = [\pi . t . V_g/2R] - \pi . y/2R = (\pi/2R) . [t . V_g - y]$;
   $\delta = 0$, until the spray spot edge C crosses the slit edge B_1B_1'
3. The total mass of particles at any given 'θ' & 'δ', M = [N. m_p].[Effective Area spraying through slit];
   $= [N. m_p].(R^2/2). [2 (\theta-\delta) - (\sin 2\theta - \sin 2\delta)]$
   Where mass of a single particle, $m_p = [(4/3).\pi.r^3] . [\rho]$; ρ is density of powder particle, r is the radius,
   N is the no. of particles sprayed at any slit width 'y'
4. Number of powder particles passing through the slit at effective spraying area
   $N = [3.m_{powder}.(2R+y)]/4.\pi. \rho. V_g.r^3$; where m_{powder} is powder flow rate (g/min) at the given spray system
5. Therefore the K.E of powder particles making impact through effective area ($BB'B'_1B_1B$) is,
   $E = [(1/2).M.V^2] = (1/2) . [N. m_p].(R^2/2). [2 (\theta-\delta) - (\sin 2\theta - \sin 2\delta)] .V^2$, where V is the velocity of sprayed particle

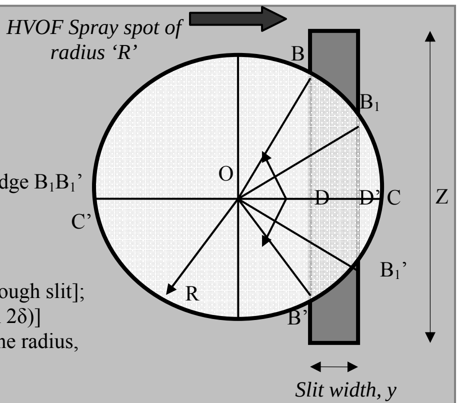

Fig. 8. Geometric model for total particle kinetic energy passing through slit.

Assuming that a constant proportion of this kinetic energy is recorded at the sensor, the function *E(t)* ought to be of similar shape to the AE energy pulse observed as the spray passes over a slit. A representative curve fitting of recorded AE amplitude to the theoretical kinetic energy distribution is shown in Fig. 9. In this calculation, the diameter of the spray spot was 10mm; the diameter of powder particles, 45µm; the density of powder particles, 4.4g/cm^3; the total number of powder particles passing through a slit of width 3mm was 3303 at the gun transverse speed of 250mm/sec; powder flow rate of 80g/min and velocity of sprayed powder particle, 800m/sec. The length of time taken for the spray gun to pass a slit at the speed of 250mm/sec is 0.052sec and it is seen that the number of powder particles increases and decreases as discussed in above formulation. Whereas a good fit is achieved for the actual, smoothed data over the calculated exposure duration of around 0.05sec, it is clear from Fig. 9, that the pulse is, in fact wider than the calculated time. This could be due to fanning of the spray, a non-uniform particle density distribution over a wider spot size and/or diffraction effects at the slit. Nevertheless, it is obvious that the model, with appropriate modifications, will serve as a useful analytical aid.

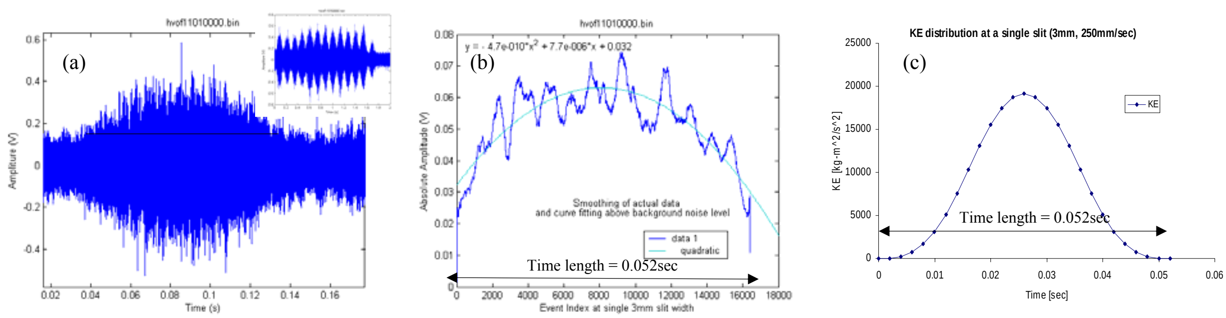

Fig. 9. (a) AE signal at a single slit of width 3mm when HVOF sprayed at 250mm/sec gun speed (see inset: full AE signal), (b) Curve fitting done on smoothed AE data of the absolute amplitude of (a), and (c) SPRAE model: Kinetic energy 'E(t)' distribution due to particle impact

Conclusions

A novel approach using AE sensors to monitor the HVOF process has been demonstrated. Whereas, the work is of a preliminary nature, the following conclusions can be drawn:

1. AE due to particle impact has been measured during HVOF spraying with WC-10Co-4Cr powders with an SNR of 3.
2. There appear to be four main frequency bands of interest; 100-200 kHz, 300-400 kHz, 550-650 kHz and 750-850 kHz, some of these relating to noise from the flame, and the remainder being associated primarily with particle-surface encounters.
3. When the fuel pressure is reduced values of various AE parameters fall, explicable in terms of the reduction in mean particle velocity.
4. For spraying through slits, as gun speed increases values of AE parameters fall, explicable in terms of reduction of mean particle density per unit time landing on the surface.
5. For continuous multi-layer spraying the general level of AE energy increases as the number of layers (and sample temperature) increase. Whereas the resulting microstructures have not yet been examined, it would appear possible that some of the AE emanates after particles have landed on the surface, possibly from micro-cracking.
6. A simple kinematic model has been shown to provide a useful framework for evaluating the results and this will be developed further.

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