ENSURING DRILL QUALITY IN COMPOSITE MATERIALS USING ACOUSTIC EMISSION

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Abstract

Acoustic emission (AE) was used as a monitoring tool for the drilling process in a carbon fiber composite material. The root mean square (RMS) of time driven AE data (TDD) and time-frequency analysis of continuous wavestream data (CWS) were used to indicate drill bit condition and to detect induced damage during the drilling process. The AE technique is shown to be a useful tool for characterising the drilling process in composites and could be used to support process optimisation or for in service quality control.

1. Introduction

The joining of composite components is an increasing requirement in the aerospace industry with both the Boeing 787 and Airbus A350 utilising ~50% composite materials by airframe weight. Despite the attraction of bonding as a joining approach, a suitably reliable method has yet to be demonstrated. Hence drilling and bolting remains the primary method used by the aerospace industry for joining composite components, with approximately 10,000 holes required for the assembly of an aircraft such as the Boeing 787 [1]. The drilling of composite materials is a critical process that if done incorrectly can introduce damage in the vicinity of the hole, reducing its strength and fatigue life. This criticality is reflected in the significant training that operatives are required to undertake before being allowed to drill composites as part of the aircraft production line. Therefore it is essential for aircraft manufacturers to ensure that holes are completed to a high standard, because any errors may lead to large and expensive components becoming dangerous and unusable. Often this is achieved through time consuming NDT and experimental programmes to optimise drilling parameters.

Acoustic emission (AE) is a passive NDT technique that relies on the detection of transient elastic waves released by physical phenomenon such as damage growth and friction. The elastic waves released can be detected by surface mounted piezoelectric transducers and stored for analysis. The passive nature of the technique lends itself well to the monitoring of continuous and dynamic processes and has been used widely to monitor machining processes in metals [2]. However, few examples of its application to the drilling process in composite materials exist [3,4,5].

In this paper the authors explore the use of the AE technique as a monitoring tool for the drilling process in composites. The root mean square (RMS) of time driven AE data (TDD) and analysis of continuous wavestream data (CWS) are used to indicate drill bit condition, to monitor wear and to detect induced damage during the drilling process.

2. Background

2.1. Drilling of composite materials

The drilling process in composite materials can induce a number of damage mechanisms including delamination, fiber pull out and thermal degradation. Delamination is the least desirable and is generated by two mechanisms: peel-up and push-out. Peel-up occurs at the drill entry where a peeling force is generated by the drill bit flutes and push-out occurs near the drill exit where the remaining material can no longer support the applied thrust force. In practice push-out delamination is normally observed to be more severe [6], hence the thrust force must be kept below the inter-ply bonding strength. The thrust force can vary with cutting speed, feed rate, drill material and drill geometry and the inter-ply bond strength will vary between materials [7], making the optimization of drilling conditions very challenging. The thrust force has also been shown to increases with tool wear [7], making tool life very important in such a highly abrasive material.

Cutting temperatures may become very high in carbon fiber composite materials. Due to their abrasive nature significant frictional heating can occur and their relatively poor thermal conductivity allows localized heat build-up. The cutting temperatures have been observed, using embedded thermocouples, to exceed 300^{o}C in some cases [8,9] but agreement on how the cutting parameters affect the observed temperature is not seen. With few aerospace composites having glass transition temperatures greater than 200^{o}C, there is real potential for thermal degradation to occur during the drilling process. This can lead to pyrolysis (decomposition) of the resin or a reduction in its properties local to the hole. The softening of the resin at elevated temperature can also reduce the inter-ply bond strength, reducing the thrust force at which push-out delamination will occur.

2.2. AE monitoring of composite drilling

The drilling process in composite materials has previously been monitored using AE by a small number of groups. Ravishankar et al conducted two studies in glass fiber materials made using a wet layup technique [3,4] and as such are not representative of aerospace materials. They used both the power spectral density (PSD) of burst AE and the RMS of TDD AE data to analyze the drilling process. The use of burst emissions to monitor a continuous processes can be limited, because data are collected as short and discrete packets that represent only a small proportion of the overall process, hence there is a risk of missing important events such as delamination. The PSD of AE signal may also be misleading because the frequency of the continuous cutting process will dominate and can mask singular events at different frequencies. The use of TDD is far more appropriate for monitoring continuous processes but finer details of singular events may again be masked due to the averaging effect of the RMS calculation. Mascaro et al [5] captured CWS AE data whilst drilling aerospace grade carbon fiber composites, but due to equipment limitations their acquisition duration was limited to 20ms and 5 separate wavestreams were collected during each drilling process. They used PSD and short-time FFTs (STFFT) to differentiate between drilling of titanium and carbon fiber and to indicate tool wear.

3. Drilling experiments

All the drilling tests undertaken were conducted on quasi-isotropic carbon fiber composite manufactured from 30 plies of Umeco MTM28-1/T800H/12(k)/120/40%RW uni-directional material with a thickness of 3.95mm. The material was autoclave processed with a cure temperature of 120^{o}C. Coupons were cut from this material to a size of 50 x 50mm and were held in the test fixture shown in Figure 1, which was mounted in a three-axis milling machine via a dynamometer to record thrust force. The fixture has 10mm diameter clearance holes behind each of the five drilling positions visible and a cantilever clamp to secure the AE sensor. AE data were recorded using a Mistras Pico miniature sensor that has an operating frequency range of 200-750kHz, a resonant frequency of 500kHz and dimensions of 5mm dia x 5mm. The sensor was mounted directly to the surface of each coupon, using general purpose brown grease as an acoustic couplant and correct attachment was verified using a Hsu-Nielsen source. The RMS of the sensor output was monitored throughout the drilling process using a time window of 10ms. The CWS data were recorded for a 10s period with a sample rate of 5MHz and the dynamometer force output was recorded for a 20s period with a sample rate of 1kHz. Both were triggered manually at the start of each drilling test.

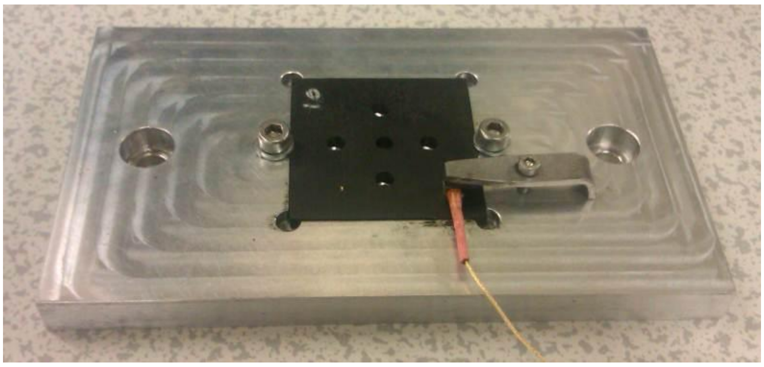


Figure 1. Test fixture and composite coupon after drilling.

3.1 Study one

An initial study was undertaken using artificially deteriorated drill bits to assess the potential for AE to determine drill bit condition. Three standard 5mm diameter carbide twist drills with an 118^{o} point angle were used; one remained pristine, a second was artificially blunted by grinding and a third was artificially damaged by grinding a notch from one cutting edge to represent a chip. A central hole was drilled in five samples with the pristine bit and four samples each for the blunt and damage bits. A spindle speed of 2000rpm and a feed rate of 0.1mm/rev were used in all cases.

3.2 Study two

A second study was undertaken to monitor the natural deterioration of drill bit condition over a series of drilling tests, to generate a realistic data set. High Speed Steel (HSS) bits were used due to their reduced wear performance compared with carbide bits, allowing a study of the wear process to be undertaken across relatively few holes. The drill bits used were again 5mm diameter twist drills with a 118^{o} point angle. In this study a pristine drill bit was used to drill 24 holes in the previously used samples; four additional holes were drilled in each sample, as shown in Figure 1. A spindle speed of 2800rpm was used and a slower feed rate of

0.0254mm/rev was used to further promote the wear process. Time driven AE data, CWS data and thrust force were recorded for all 24 holes drilled.

4. Results and discussion

The results will be discussed in relation to four key positions in the drilling process which are: 1 - first contact of drill point with composite surface, 2 - full engagement of the cutting edges in the composite, 3 - drill point reaching the back surface and 4- complete breakthrough of the full drill diameter. From position 1-2 an increasing amount of cutting face is engaged with the material and therefore an increasing amount of material is cut with each rotation. From position 2-3 is a continuous process with the same amount of material cut with each revolution. From 3-4 the amount of material cut decreases as the bit begins to break through the back surface.

4.1 Study one

Figure 2. shows the peak RMS value observed during the continuous cutting phase, between drilling positions 2 and 3, for the three drill bit conditions. There is a clear separation between the peak RMS levels observed for each drill bit condition used, demonstrating the ability to reliably determine drill bit condition. The damage drill bit produces the largest peak RMS and the blunted drill bit producing the lowest. It is somewhat counter intuitive that the blunt drill produces the least energy, given that a blunt drill will not cut well and is more likely to induce greater damage. However, the elevated temperatures observed by others [8,9] are far in excess of the cure temperature for the resin system used here (120^{o}C). It is therefore highly feasible that the resin is softening, prohibiting the formation of chips through brittle fracture and instead a more ductile cutting process is occurring, which will produce less AE energy.

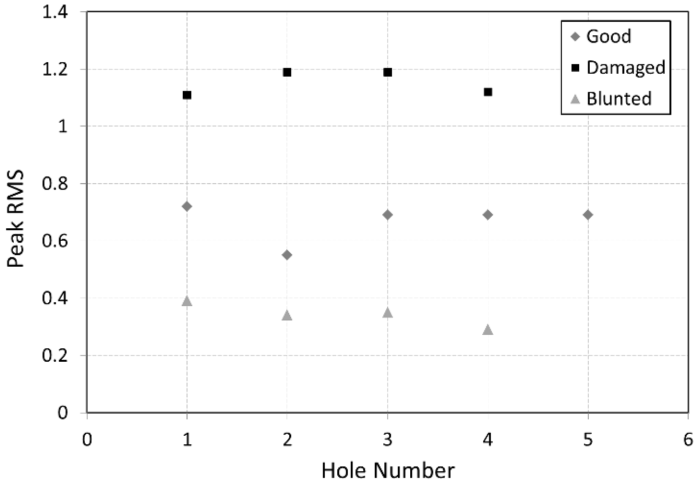
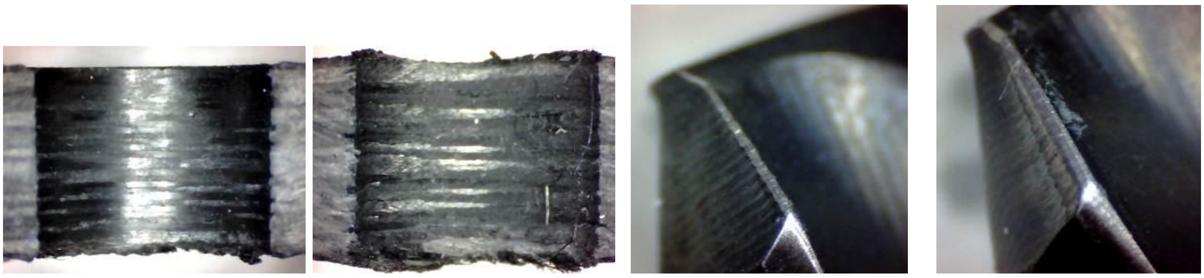


Figure 2. Peak RMS values versus drill bit condition for good, blunt and damage drill bits.

4.2 Study two

Images of two holes drilled in the second study and the cutting edges of the HSS drill bit used are presented in Figure 3. The wall of the first hole drilled (a) has a smooth surface, there is no evidence of peel up and very little evidence of push out damage; indicating that the hole has been well drilled. After drilling eighteen holes the surface has become noticeably rough (b) and an increase in thickness is observed from peel up and push out mechanisms; indicating that the quality of drilling has reduced due to blunting. Wear was visible on the cutting edges after drilling as little as four holes (c) and significant wear was present after completing all twenty four holes. Figure 3d also shows a buildup of resin and fiber debris along the cutting edge, suggesting the resin may have been soft or melted and has become adhered to the cutting edge; supporting the hypothesis that local heating from friction is occurring. The continued deterioration of the drill bit is also evident in the dimensional tolerance of the holes (Figure 4.). The sample thickness is seen to increase by over 0.6mm at the hole due to pull up and push out induced damage and the diameter is seen to reduce by over 0.16mm from the required 5mm. Closer inspection of the walls in the latter drilled holes reveals a large amount of protruding fibers, which when no longer supported by the softened resin are more readily bent and pushed aside as opposed to being cut. Following withdrawal of the drill bit the fibers spring back, therefore reducing the dimension of the drilled hole.



a) b) c) d)

Figure 3. Microscope images of a) the first hole drilled, b) the eighteenth hole drilled, c) the drill bit cutting edge after drilling four holes and d) the drill bit cutting edge after drilling 24 holes.

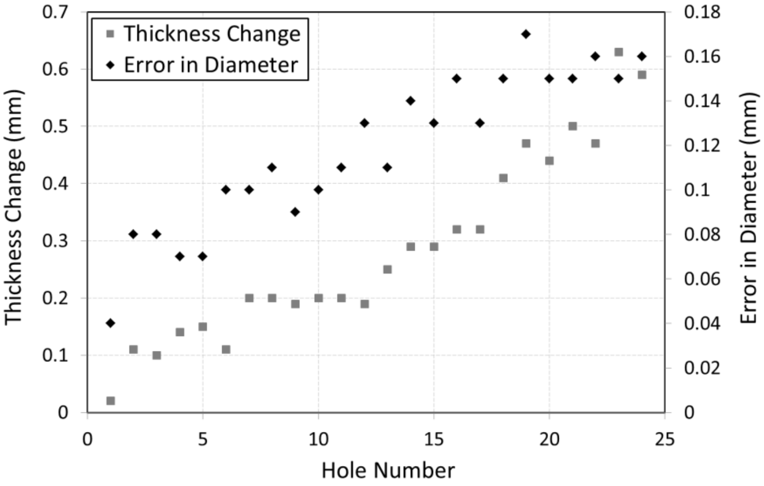


Figure 4. Change in sample thickness and reduction in diameter versus number of holes drilled.

Concurrently with the observed wear process, an increase in observed thrust force was experienced as the number of holes increased (Figure 5), as would be expected for a drill bit that is becoming increasingly blunt. The wear process observed is also clearly detected by a corresponding reduction in the average RMS level (Figure 5), measured between drill positions 2 and 3, which is consistent with the reduced RMS level observed in the blunted carbide bit (Figure 2). Thus demonstrating that AE can be used to detect and monitor the tool wear process during the drilling of composite materials. The greatest change observed in both thrust force and RMS is seen over the course of the first five holes, indicating a very rapid wear process is taking place and highlights the abrasive nature of the material.

The RMS of signal level has proven to be a very useful technique for detecting wear during the drilling process, however, due to the averaging effect of the calculation finer details within the AE transient may be overlooked. The passive nature of the AE technique means a continuously recorded transient will contain information about all of the mechanical processes taking place, including friction, cutting, delamination, fiber pull out etc. Therefore more thorough analysis of CWS data may reveal more detailed information about the drilling process. Figure 6 a and b present two CWS for the first and eighteenth holes drilled, respectively, where the vertical black lines indicate the four described drilling positions. Also presented are the approximate entropy (ApEn), the RMS values and a time-frequency representation of the raw signal. Approximate entropy is a statistical approach that provides a measure of the regularity of fluctuations within a time series. In this case the ApEn value is calculated over a 500 sample (or 100µs) window and the window is shifted along the signal with zero overlap. Low values of ApEn correspond to greater structure, or regularity, within the signal. The time-frequency representation is given by a Gabor wavelet transform and due to the high computational demands the signal was segmented into five consecutive series that were processed separately and then subsequently stitched back together for visualization.

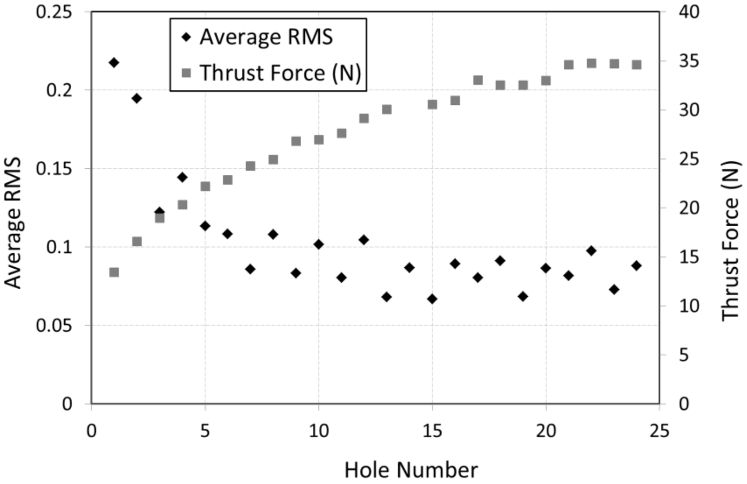
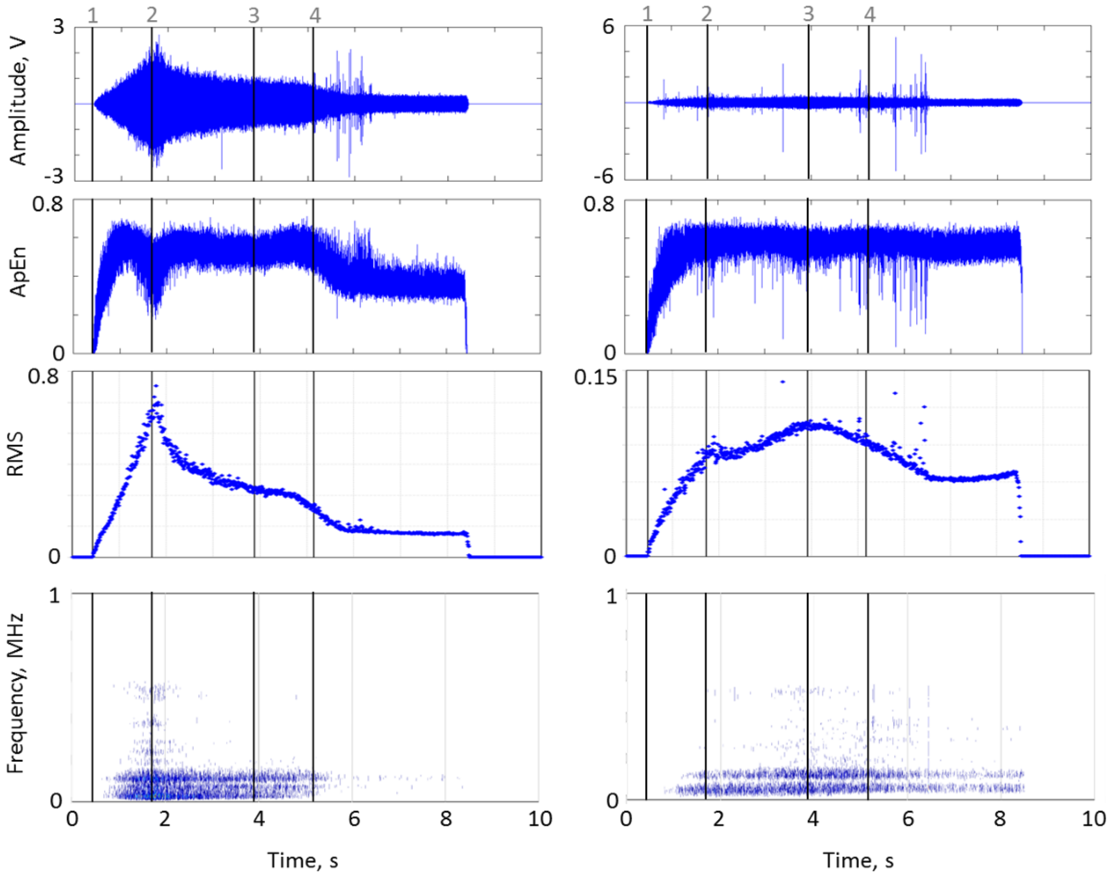


Figure 5. Average RMS value and peak thrust force observed versus number of holes drilled.

Consideration of the two CWSs presented in their raw form in Figure 6 reveals a number of observable differences; however the reader should note the differing scales on the presented transients. In the case of the first drilled hole the signal amplitude steadily increases until drilling position 2 where the cutting edges are fully engaged and following this point the amplitude is seen to reduce gradually. This can be attributed to the rapid wear of the drill bit and shows that wear is already beginning during the first hole drilled. This behavior was not seen when using carbide bits, with significantly better wear properties, for which the amplitude increases until position 2 and then remains constant. For the eighteenth hole the amplitude rises until position two and then remains constant. The CWSs also show the presence of short, individual and higher amplitude peaks. For the first hole these are only visible after full break out of the bit and are likely to result from the clearing of material debris from the break out. However for the eighteenth hole these peaks are visible throughout the drilling process and particularly just prior to full break out where the likelihood of inducing delamination is greatest. The observed change in signal amplitude is clearly represented by the RMS data presented and in addition the more significant of the peaks observed for the eighteenth hole are also captured by the RMS data as high value individual readings.



a) b)

Figure 6. Continuous wavestream analysis including the raw signal, the windowed approximate entropy, the windowed RMS and a wavelet time-frequency analysis for a) first drilled hole and b) the eighteenth hole.

The approximate entropy is a particularly useful tool for the analysis of the CWS and it can be seen that the average ApEn value rises to a level of ~0.6 in both cases, where it remains throughout the cutting process. The key difference is the repeated lower values present for the eighteenth hole that are not seen in the case of the first hole. Many of these align with the peaks observed in the CWS and indicate bursts of structured AE that may come from such sources as delamination and fiber breakage, overlaid on the more random AE that occurs from cutting and friction sources. This approach may prove useful for identifying the occurrence of specific events within the drilling process and enable the detection of induced damage.

The time-frequency analysis shows a dominant frequency band below 200kHz in both cases, that occurs throughout the drilling process; hence it can be related to the cutting process and friction mechanisms that occur. For the eighteenth hole energy at this frequency continues well beyond the break out of the drill and continues until the drill bit is withdrawn, indicating the presence of greater friction from the uncut fibers present. It is also noted that this frequency band is below the sensitive range of the sensor, helping to reduce the dominance of the lower frequencies in the data collected. This allows more obvious detection of the higher frequency components and the time frequency analysis also allows far better visualization of these frequencies when compared with PSD plots. Higher frequency contents is observed around position 2 for the first drilled hole and following position 2 for the eighteenth hole. It is hypothesized that higher frequencies result from brittle fractures, which will be encouraged by the sharp cutting edge and low temperatures at the start of the first hole. The presence of significant higher frequencies for the eighteenth hole indicates that damage may be induced, such as delamination from increased thrust force and fiber breakage from displaced fibers. This would mean that manufacturers could monitor specific frequency bands and use a threshold approach to alert them to any problems arising. For example a reduction in energy at low frequency would be linked to drill blunting and increasing energy at higher frequencies would be linked to damage initiation.

5. Conclusions

It has been demonstrated that the AE technique can provide a very powerful tool in the understanding of the drilling process in composite materials. It has great potential to support testing programs for the optimization of drilling parameters and could be used for in service quality control, giving real time feedback on hole quality to operatives.

The AE technique proved very sensitive to wear processes and it was demonstrated that drill bit condition can be accurately assessed through consideration of signal RMS. The analysis of CWS data demonstrated that much greater detail can be drawn from the data set when compared with RMS alone. The occurrence of specific events can be identified using approximate entropy and can highlight when damage is occurring in the drilling process. The use of time-frequency analysis demonstrated the low frequency characteristic of cutting and frictional sources and allowed the identification of lower energy high frequency components.

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