Detecting Thermal Crack Growth on a Large Additive Manufactured Structure using Acoustic Emission

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ABSTRACT

Large format additive manufacturing (LFAM) proved to have a great potential to become an adjacent technology to traditional manufacturing methods. One of the sectors LFAM is targeting is rapid tool/mold development for composites. This includes large mold structures used for high-temperature molding techniques (in-oven or autoclave). Although, these large printed structures (reaching hundreds of pounds) develop thermal-residual stress during cool-down and can eventually crack, turning the structure into waste. Acoustic emission (AE), a passive non-intrusive global nondestructive evaluation (NDE) technique, was used to monitor crack growth and can provide the right tools that can be used for feed-back loop for corrective action. This research performs thermal testing on a large AM mold with preexisting cracks, in an attempt to monitor crack growth using AE. AE was able to detect, identify and locate the crack source by means of acoustic features, waveform characteristics, spectrum analysis, and difference in arrival times.

Keywords: Large Format Additive Manufacturing, Acoustic Emission, Nondestructive Evaluation

1. INTRODUCTION

Additive manufacturing (AM) has provided the opportunity to construct complex geometries efficiently by performing a layer-by-layer fabrication process. AM was initially used for rapid prototyping, but is rising to construct in-use structures such as tooling/molds for composite layup. Large format additive manufacturing (LFAM) is targeting rapid tooling [1, 2], autonomous vehicles [3], and rapid boat construction [4]. The current state-of-the-art maximum printing rate is 227 kg/hr (500 lb/hr) for the largest polymer LFAM machine with a build envelope of 7.6 m wide, 30.5 m long, and 6.1 m tall (25 ft x 100 ft x 20 ft) [5]. These LFAM machines are fabricating complex structures, that in some cases requires an expensive feedstock material and extended number of printing hours. It is critical to detect anomalies and defects at early stages of the manufacturing process. Detecting anomalies at this stage will allow for corrective actions or stopping a failed print resulting on a significant savings on material, time, and cost.

Nondestructive evaluation (NDE) is the field of detecting defects and anomalies without using invasive measures on the material or process. Defects which are still prevalent in AM are warpage, layer separation, internal voids, and cracking [6]. There have been multiple NDE techniques that have been used to inspect and monitor LFAM including ultrasound [7], infrared thermography [8, 9], and digital image correlation [10]. Acoustic Emission (AE) is a passive NDE technique that utilize an array of piezoelectric sensors to monitor and detect stress related excitations caused by source defects such as cracks and layer separation [11]. AE is traditionally used to perform structural health monitoring (SHM) on bridges [12], generators [13], and wind turbines [14]. It has also been used to characterize reinforced composite material including fatigue testing [15], impact detection [16], and fiber fracture [17]. To the best of the author's knowledge, there has been no literature using AE for LFAM structures.

This research used AE technique to monitor crack growth caused by thermal-residual stress for a LFAM printed structure. The large printed structure had a preexisting layer separation (crack) and was placed in an oven to thermally cycle it to allow for a further layer separation - crack growth. This preliminary investigation is a proof that AE can be used to locate and characterize these kind of anomalies, thermal-residual stress monitoring and foreseen as an in-situ technique.

2. EXPERIMENTAL SETUP

The AM structure was printed on the Big Area Additive Manufacturing (BAAM) system at the Oak Ridge National Laboratory – Manufacturing Demonstration Facility (ORNL-MDF). The BAAM equipment has the capability to extrude at 45.4 kg/hr (100 lb/hr) with a build envelope of 6.1 m x 2.4 m x 1.8 m (20 ft x 8 ft x 6 ft). The print material is a polysulfone-polyethersulfone blend (PSU-PESU) reinforced with 25% fiber-weight-fraction carbon fiber (PSU-PESU/CF). A PSU-PESU/CF structure was printed for a tooling application. After printing, the structure was allowed to cool at ambient temperature (73 ºF). After cooling, two large cracks occurred due to the thermal-residual stresses from a nonoptimized print process. Two layer separations (crack 1 and 2) occurred and had sizes of 40 to 46 cm in length, see **Figure 1**. It must be understood the crack could be longer in length where layers are in contact and are not visible to the naked eye but have little to no interaction or strength.

The structure was put through a heat cycle to further the crack propagation to evaluate the AE system ability to capture and quantify the crack growth. The AE monitoring was performed using a MISTRAS Group, Inc. Micro-II Digital AE system using PK6I AE sensors. The AM structure was instrumented with eight AE sensors and three K-type thermocouples to monitor the two cracks and structure's temperature, respectively, shown in **Figure 1**. The AE sensors were separated into two groups to monitor each individual crack (Group 1: S1-S5 monitoring C1, Group 2: S6-8 monitoring C2). A National Instruments DAQ system with an NI-9217 card was used for temperature measurements. A walk-in oven (GRIEVE TB-500) was used for the thermal cycle, shown in **Figure 2**. The AM structure was placed in the oven with slip pads underneath to reduce frictional noise and allow thermal expansion. The thermal cycle procedure, as seen in **Table 1** and **Figure 3,** where the oven was initially ramped to 45 ºC for a two-hour dwell, then ramped to 75 ºC for another two-hour dwell, and then finally allowed to cool down to room temperature. Pencil lead breaks (PLB) were performed before and after the test to confirm each sensor's sensitivity.

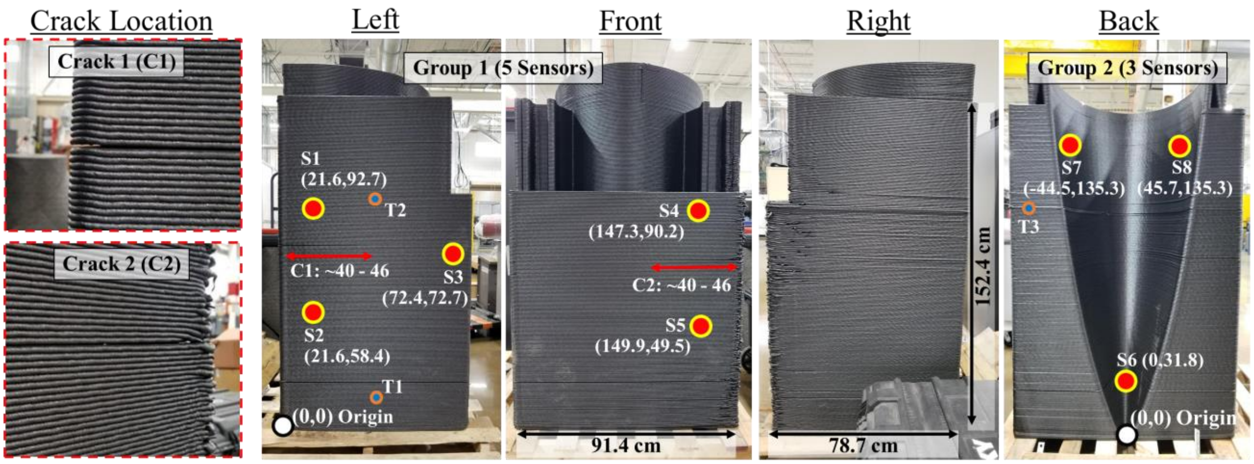

Figure 1: Large AM structure with pre-existing crack locations (C1 & C2) measuring 40 - 46 cm in length for each. Associated AE sensor locations (Group 1 and 2) to monitor crack growth in corresponding locations. Thermocouples (T1-T3) monitor temperature. Units in cm.

Figure 2: Thermal cycle setup with GRIEVE walk-in oven, thermocouple DAQ system, and the AE system. The AM Structure was placed on smooth slip pads to allow thermal expansion and reduce frictional noise.

Table 1: The thermal cycle procedure for AE monitoring

	Thermal Cycle Procedure Description
1	AE Sensor PLB Test – Before
2	AE & Thermocouple DAQ System ON
3	Oven ON – Ramp to 45 ºC, dwell 2 hours
4	Ramp to 75 ºC, dwell 2 hours
5	Oven OFF – Cool down
6	AE & Thermocouple DAQ System OFF
7	AE Sensor PLB Test – After

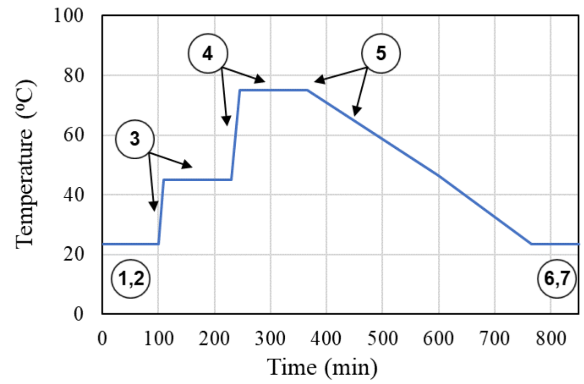

Figure 3: The thermal cycle graph from the thermal cycle procedure (**Table 1**).

3. RESULTS AND DISCUSSION

Multiple AE events were captured during the heat cycle of the printed structure. **Figure 4** shows the captured AE amplitude events along with the temperature of the structure over the time duration. Event 1 occurred right after the initial ramp up at 35 ºC. Event 2 was captured right after the second ramp up at a temperature of 63 ºC. Then, Event 3 occurred around 3.5 hours into the cooling stage where the structure was at 64 ºF. From the results it can be noticed that ~64 ºF can be corelated to layer separation for this print material and structure. The amplitude for Event 1, 2, and 3 were 99, 90, and 96 dB, respectively. Other events were captured but are related to noise features based off of low amplitude response and waveform analysis.

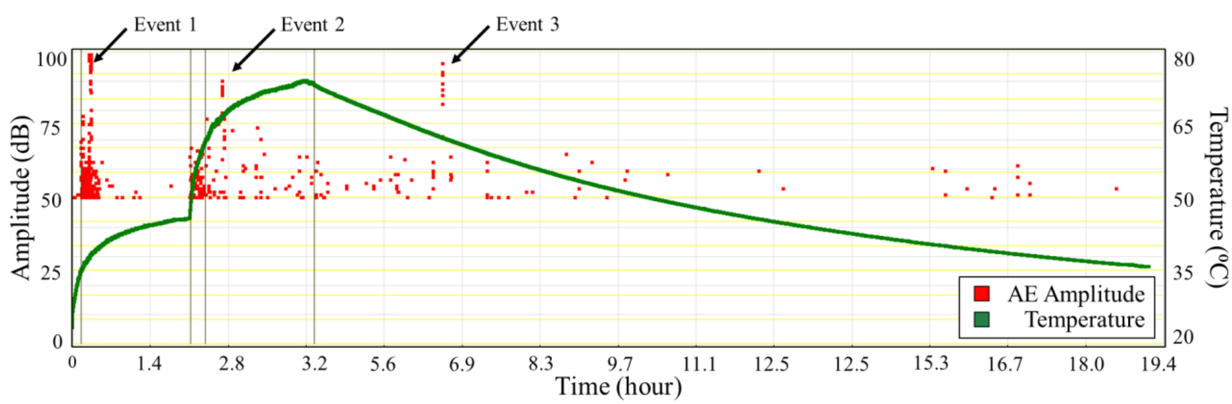

Figure 4: AE Amplitude vs Time with temperature parametric during the heat cycle. Events 1, 2, and 3 correlating to crack propagation/nucleation on the AM structure.

Figure 5 displays Event 1, 2, and 3 waveforms and spectrum analysis. Event 1 and 3 had a broad band frequency response (0 kHz – 220 kHz) including higher frequencies (above 150 kHz). Event 2 had a mid-frequency response (0 kHz – 125 kHz). High-frequency responses in polymer composites are related to fiber breakage, mid-frequencies correlate to delamination and interfacial debonding, and low-frequencies are from matrix cracking within traditional laminate composites [18]. Event 1 and 3 can be correlated to layer separation along with fiber breakage due to the presences of high amplitude with mid-to-high frequency response. Event 2 can be characterized as layer separation due to its medium amplitude and mid-frequency response.

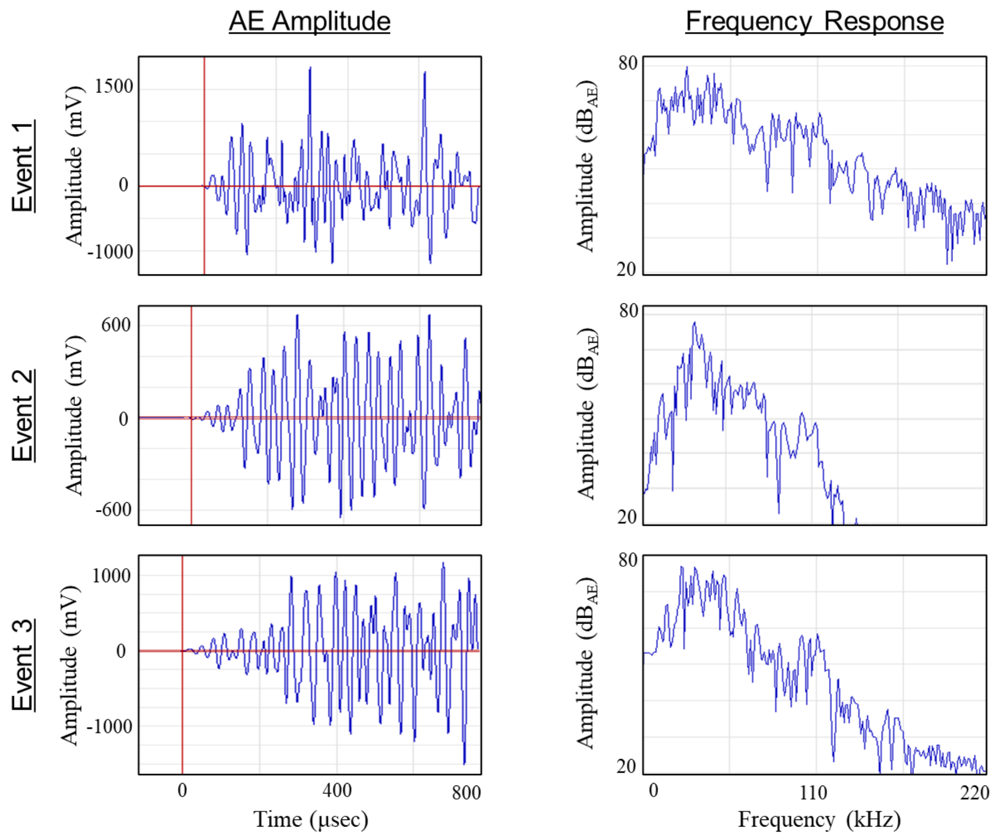

Figure 5: The AE amplitude and frequency response for Events 1, 2 and 3.

AE has the ability to pin-point event locations with a 2D planar array of sensors. This is performed by difference in arrival time (Δt) calculations when the materials acoustic velocity is known and ratios of time are related to AE sensor position distances [19]. The PSU-PESU/CF printed structure has anisotropic acoustic properties. The acoustic velocity along and transverse the print bead direction is 3220 m/s and 1670 m/s, respectively. These velocities were input into the AEwin software, along with the structure's overall geometry and sensor positions on the structure to determine event location relating to the crack growth, shown in **Figure 6**.

The continuation of crack 1 (C1) was captured in Event 1 and 2 with XY locations of 59.9 cm, 73.8 cm and 50.9 cm, 76.7 cm, respectively, within Group 1. Crack 1 had an initial length of 40 cm to 46 cm in in length (X direction) and seems to continue to a length of ~50 cm to 60 cm. The initial length was visually performed and may not have been the true starting length. It can be hypothesized with some confidence Events 1 and 2 are capturing crack 1 continued layer separation. For crack 2, no crack propagation was captured by AE due to lack of amplitude response typically associated with crack propagation. It can be notice there were other multiple events captured in the Group 1 location plot, but have been classified as low-level events (noise) when viewing the Amplitude-Time plot (**Figure 4**) and individual waveforms. Group 2 within the conical geometry of the AM structure captured Event 3 with a position of -39.1 cm, 125.9 cm. No preexisting crack was visually found in this location before the thermal cycle.

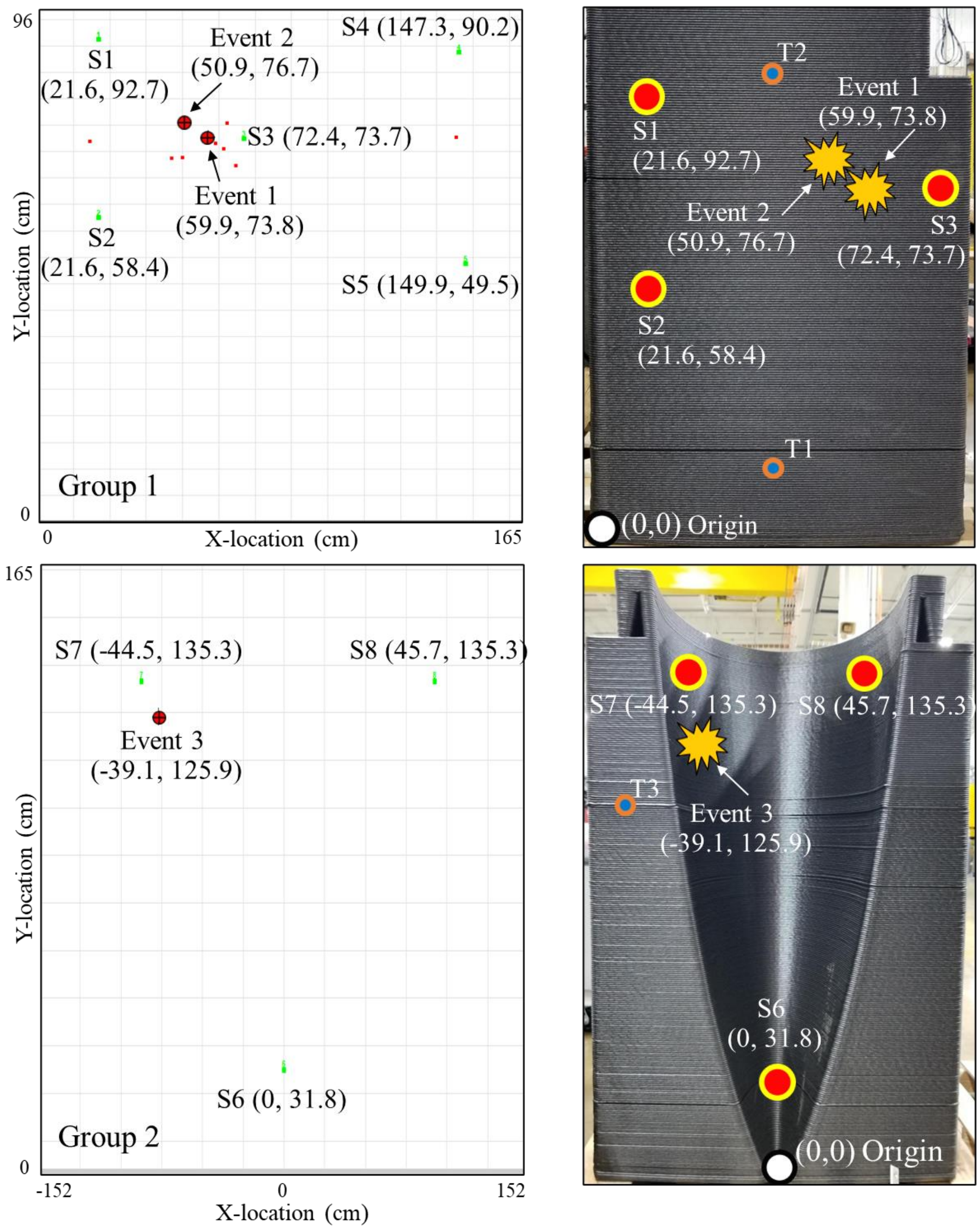

Figure 6: AEwin crack location within Group 1 and 2. Group 1 captured the continuation of crack 1 with Events 1 and 2. Group 2 captured a new crack anomaly with Event 3. Sensors and events overlay on AM structure. Units in cm.

This work focuses on the preliminary findings of the validity of using AE to monitor large composite AM structures for thermal-residual cracking, however, it is suggested to cross-verify AE results with other NDE techniques, such as in-situ digital image correlation [20, 21] or ultrasound testing [7]. It is suggested to investigate if the acoustic responses (amplitude, frequency, etc.) for damage characterization (fiber breakage, matrix cracking, and delamination) of discontinues reinforced composite materials used for AM structures.

4. CONCLUSION

AE was able to capture and locate continued layer separation from a large AM structure during an induced thermal cycle. The continuation of a layer separation (crack 1) was characterized by two events: Event 1 had high amplitude and mid-to-high frequency which describes fiber breakage and interfacial debonding, while Event 2 can be described as purely interfacial debonding due to the medium amplitude and mid-frequency response. The locations of these events is placed at the tip of the measured crack length, describing continuation of the layer separation. A newly developed crack nucleation was captured by Event 3 located within the conical geometry of the structure. The crack growth can be described as layer separation due to the high amplitude and high-frequency response. These preliminary findings display the ability of AE to monitor large AM structures for thermal-residual cracking. AE can be used as a NDE technique to provide quality assurance for AM structures. This can overall save time, costs and efforts.

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