Solid Freeform Fabrication 2018: Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

ACOUSTIC EMISSION TECHNIQUE FOR ONLINE DETECTION OF FUSION DEFECTS FOR SINGLE TRACKS DURING METAL LASER POWDER BED FUSION

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Abstract

One of the main drawbacks of laser based powder bed fusion, is lack of fusion between tracks due to non-optimal input process parameters, scanning and building strategies and/or inhomogeneity in the delivered powder layer. Unstable geometrical characteristics of single tracks and high roughness of the powder layer can cause porosity in 3 dimensional printed parts. In this study a non-destructive online monitoring technique, using acoustic emission was utilized to determine lack of fusion and balling effect of single tracks. This phenomenon was simulated by using an increased powder layer thickness. Short Time Fourier Transform was used as a tool for analysis of the acoustic behaviour of the system and it was compared with the acoustic emission (AE) recorded during processing of single tracks.

Introduction

Laser based powder bed fusion (LPBF) is an additive manufacturing (AM) process in which thermal energy from a laser beam selectively fuses regions of a powder bed [1]. The benefits of LPBF are: high degree of design optimization derived from shape complexity; possibility to produce complex lattice and combined structures; relatively high resolution, limited by laser beam size and powder-based properties; re-usability of powder material; etc. But due to the track-by-track, layer-by-layer nature, LPBF has drawbacks such as: bad surface finishing, size and design limitations - especially for overhanging parts; high thermal gradients which cause residual stress that can result in the formation of internal cracks and deformations during processing; non-optimal input process parameters such as scanning and building strategies or inhomogeneity in delivered powder layers cause porosity in LPBF parts; defects cause a substantial deterioration in the performance properties in LPBF parts and limit wide application of this Additive manufacturing (AM) technology in the industry [2].

In-process defect sensing and control is one of the main steps for ensuring repeatability and consistency of LPBF manufacturing. Key process parameters in LPBF are: laser and scanning parameters; powder material properties; powder bed properties and recoating parameters and build environment. Process signatures emanating from the melt pools in LPBF are: molten/solidified pool; plasma emission/absorption; radiation;reflected/scattered light, *etc.*-these phenomena are the basis to control stability and repeatability of the LPBF process [3]. Visual, ultrasonic, Eddy current, radiographic, magnetic methods, liquid penetrant test, shearography, acoustic and thermography – are all NDT technique that can be used for quality control in AM [4], [5]. Thermography and acoustic emission testing are applied as inspection methods for in-situ monitoring of AM processes, but the spatial and temporal resolution of in-process monitoring with feedback depends on specific scanning parameters. LPBF is a very fast process, so on-line NDT and feedback control is extremely difficult to attain. For spatial capability, minimum AM defect size also has to be investigated in order to determine if the part is fit for service [6-7]. Available commercial LPBF monitoring systems mainly use: photodiode melt pool monitoring; CMOS camera for powder bed imaging system; as well as others methods that include the use of IR and UV photo sensors and pyrometers [3].

An in-process non-contact method could be AE - AE is seen to have high signal to noise ratio and fast response. Non-contact methods can be used for quality control of the ever growing laser technology implemented in industrial applications [8]. Palanco, *et al*. (2003)[9] studied microphone signals to monitor laser ablation and acoustic emission of plasmas . It was shown that spectral analysis of acoustic waves is a reliable technique for the diagnostics of laser plasma phenomena. Mao *et al.* [8] 1993 showed that the acoustic spectrum of conduction welding is different from that of keyhole welding and that there exists strong correlation between the AE energy signal and laser power, welding speed and focusing distance (laser spot size).

For laser sintering, surface modifications and welding, various phenomena such as: melting and solidification; vaporization; interaction of materials with protective atmosphere; shrinkage and solid-state phase transformations; plastic deformations and cracking - these are all related to acoustic phenomena. In general, qualitative types of AE signals are burst (discrete) and continuous. Delamination, crack initiation under deformation or corrosion can be qualified as energy "burst" that is emitted. Acoustic signals from diffusive phase transformations or coalescence of micro-cracks that can be classified as continuous signals [7], [10], [11]. AE in materials that undergo deformations and fractures depends on physical properties of material as well as environmental factors [12], [13]. AE testing is exceptionally sensitive when compared to other NDT techniques and can recognize crack growth of the order of 25 μm [7].

Leaks and frictions i.e. interactions of media in relative motion, chemical reactions and changes of size of magnetic domains also generate acoustic waves and create other class of AE signals that can be studied for quality control of tooling and manufacturing. Charde *et al*. [14] (2016) interpreted the weld formation using AE for the carbon steels and stainless steels welds in servo-based resistance spot welding. A typical acoustic behaviour of servo-based system was found and then AE amplitude of frequencies and corresponding phase shifts for "ideal" welding condition was received at expulsion welding conditions were analysed. It was found that different AE patterns were used to distinguish the behaviour of ideal and faulty welding processes that were qualified by macrographs. Similar results were received for laser welding of Al and Polyamide sheets by Schiry *et al*. [15] (2016). Rough joint was a result of excessive energy input. Gas bubbles provoked creation of the gas channels registered by hits-time AE monitoring during the process. Higher hits in the area of the gas channels correlated with the appearance of the holes in welding. With decreased energy input, weak joint with low pulling strength was created and AE signals were irregular and wide scattering was found. Also it was shown that the material as well as distance of the sensor to the weld spot has a strong influence to the signal.

A non-contact acoustic inspection method for LPBF was proposed by Redding *et al.*[16] (2017) - it is opposed to sensors being attached underneath the build substrate. Signal profiles for free-defect parts were compared with manufactured, qualified parts. Sudden deviations in the amplitude of acoustic signals indicated a fault in the process. A similar approach was used by Gaja and Liou [17] (2017) for defect classification of AM by direct energy deposition process - amplitude, ringdown count, duration, rise time, i.e. time dependent AE event features were collected and used for clustering analysis. Cracks and pores and their AE signal characteristics were successfully distinguished and verified by post-test optical microscopy. Fisher *et al.* [18] (2016) showed that a notable difference could be obtained from the acoustic signatures of varying laser powers during LPBF. It was found that there was a clear shift and missing peaks in spectral analysis between the two different laser powers.

AE has great potential for monitoring machine events during AM processing [4]. Combination of AE with machine learning for in-situ and real-time quality monitoring of the AM process was reported by Wasmer *et al.*[19] (2017) and Shevchik *et al.* [20] (2018). The sensor was mounted directly inside the process chamber and it was used to detect AE for in-situ quality monitoring of LPBF process. Signals were analysed by spectral and conventional convolutional neural networks. It was found that a correlation between AE signals and porosity of the samples can be made, however it was also shown that AE from the AM process was quite weak compared to a strong noisy background.

A method of analysis for AE could be a Short Time Fourier Transform (STFT) - STFT is used to obtain time-frequency analysis of data signals. STFT calculates the energy distribution in the joint time-frequency domain. STFT is accomplished by calculating the Fast Fourier Transform (FFT) of the signal in a sliding window, this window is moved across the signal to give a representation of the frequency content at that specific portion in time [21].

The goal of the study is to determine if AE can be used to detect lack of fusion and balling phenomena. Scanning on an increased layer thickness was compared to scanning on optimal powder layer thickness in order to establish the relationship between process parameters of laser scanning of maraging steel powder and AE signatures from LPBF by EOSINT M280 system (EOS, GmbH).

Materials and methods

As stated the purpose of this paper to identify a non-destructive acoustic emission technique to determine lack of fusion and balling-effect of single tracks. Firstly, balling phenomenon was simulated by increasing the powder layer thickness to 300 µm. A microphone was placed inside the chamber to optimally sample data. The next step was to put the acquired data set through a predetermined high pass filer to allow for analysis of the acoustic behaviour of the system. Comparison of AE was obtained utilizing STFT as a tool. Finally, conclusions are drawn on indicators and frequency identifiers of defects from the results of the STFT.

The experiment was done using Maraging steel with chemical composition: Fe-18Ni-Co-5Mo-1Ti being Ni 17.6%, Co 8.88%, Mo 4.85, Ti 1.06%. Samples were produced on the substrate with similar chemical composition. The building chamber was filled with nitrogen atmosphere. Three single tracks, 200 mm in length were scanned at a laser power of 305 W with a scanning speed of 1.1 m/s with an EOSINT M280 system. AE was measured using an ICP microphone having an optimal frequency range of 3.75-20 000 Hz (±2dB). The microphone was placed inside the building chamber (Figure 1).

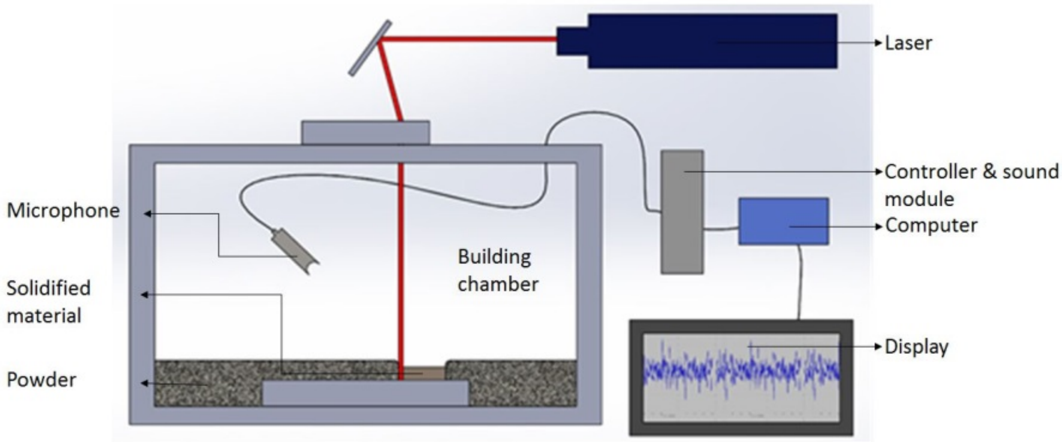

Figure 1: Schematic of the experiment

The data was acquired at a sampling frequency of 102.5 kHz. It was seen experimentally that to remove the effect of ambient operating noise that does not pertain to the actual laser scanning a high pass filter could be used. The optimal low cut off frequency was seen to be 1500 Hz. This was done by sampling a section of the recording before the tracks were scanned, applying an STFT and analysing the results.

After filtering the data signal consisted of the laser and possible AE defects. Gain control and a Short time Fourier transform (STFT) were applied to obtain the time domain as a tool to analyze and evaluate the relevant defect detections indicators.

Results and discussion

As stated, analysis, data gathering and transform processing with STFT was accomplished by track morphology and acoustic emission. Thus the result of the STFT evaluations and analysis will be used to determine markers for porosity forming phenomena, in other words fusion defects.

The result of the first step of simulated fusion and balling can be seen in the Figure 2 below, which shows the top view of single tracks at optimal and non-optimal scanning parameters.

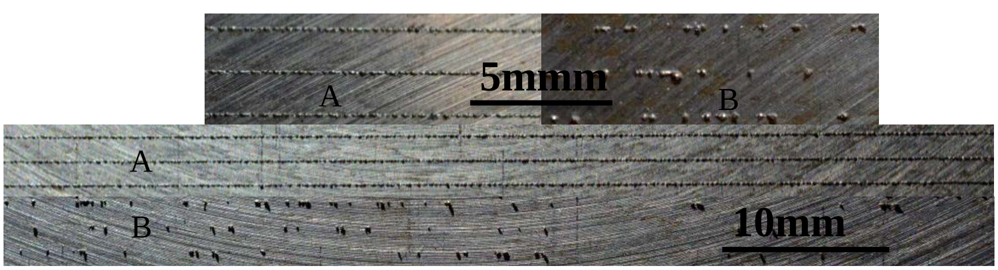

Figure 2: Maraging steel tracks on the substrate at 305 W laser power and scanning speed of 1.1m/s at 50 μm powder layer thickness (Optimal; A) and 300 μm (non-optimal; B)

The top view of the optimal process parameters show that the track is uniform and continuous, while the non-optimal shows that the track is clearly irregular and almost no track formation is present. The top two images in Figure 2 show control tracks at higher magnification. Note the three control scan tracks and the three defect scan tracks. Using STFT the three control tracks will be analyzed against the three defect scan tracks.

Acoustic emission

The figure below shows the results of the next step which is the high pass filter which is needed prior to analysis of recordings to remove unwanted environmental noises and improving the relevant signal to noise ratio.

The entire signal of the process from start to finish is shown in Figure 3. It can be seen that the EOSINT M280 has various processes that emits sound, but no clear scanning is shown until the filtering and processing is applied.

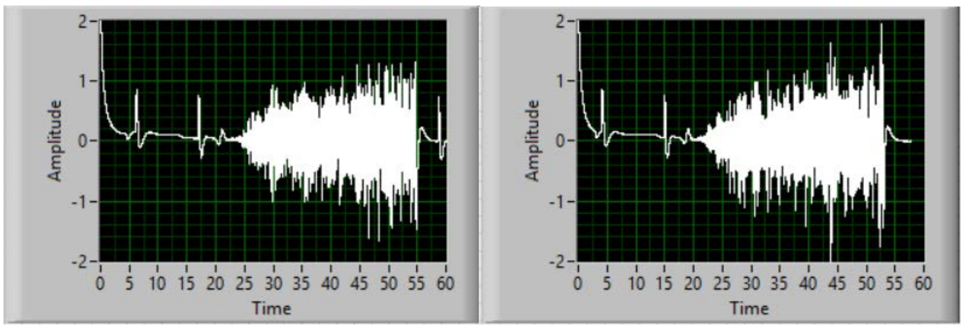

Figure 3: Graph of entire process over time optimal (left) and non-optimal (right)

The three tracks can be clearly distinguished using the high pass filter as shown in Figure 4, the time of scanning correlates to that of scanning a 200mm track at 1.1 m/s.

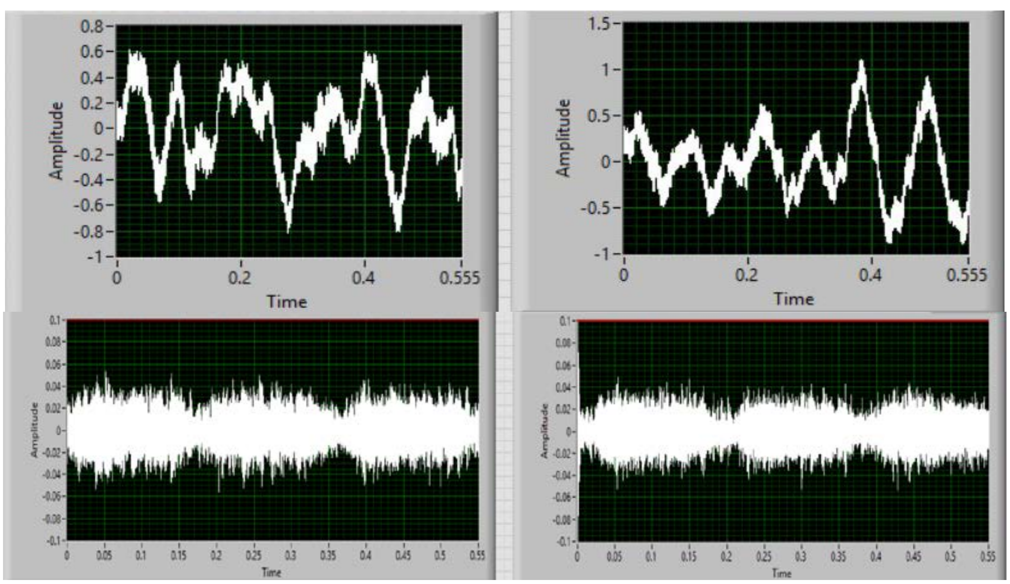

Figure 4: Signal of three tracks at optimal (left) and non-optimal (right) before (top) and after (bottom) applying signal filtering

The next step is the application of the STFT to analyze and evaluate the scan samples. Note in figure 5 that when using a Short Time Fourier Trasnform (STFT) one can clearly distinguish when scanning starts and when each track was being scanned. Figure 5 below shows a spectrogram of the three tracks in both optimal and non-optiaml cases. The spectogram is a three dimensional graph with colour indicating amplitude with blue as low values and red as high values. The y-axis is the corresponding frequencies and the x-axis the time interval of the sampled data. Each time interval on the x-axis will show the Fourier transform in a window of 102 samples and show a colour indicating the magnitude of that specific frequency in the y-axis.

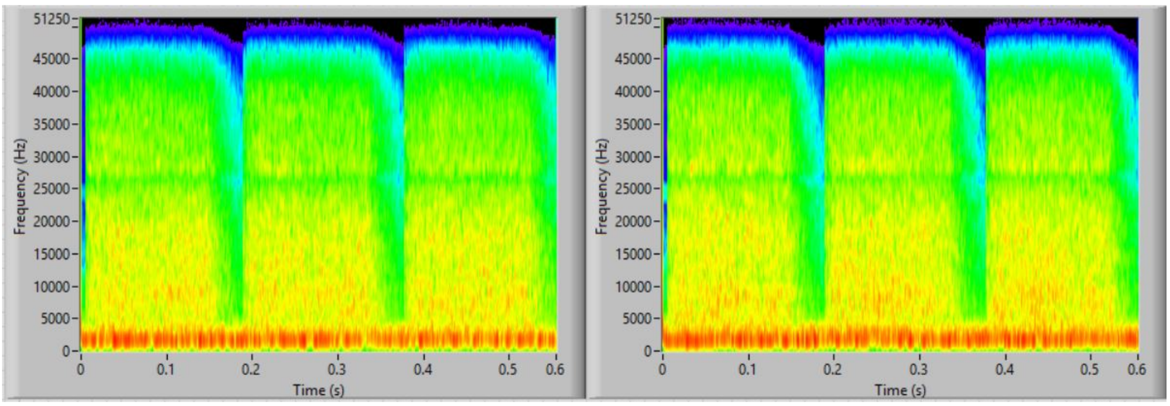

Figure 5: Spectrograms of three scans showing a decrease in intensity in non-optimal processing, optimal (left) and non-optimal (right)

In figure 5 the three different tracks can be clearly seen in the time domain - again these scanning times correlate to that of scanning a 200mm track at 1.1m/s. The frequency content of the scans is spread over the entire range of frequencies, with high frequencies being more prominent in the non-optimal scan.

The next step in the analysis is to add all the values in the individual frequencies across the x-axis together. This should give an indication as to which frequencies has the most energy or significance, with the low values of the between scans not influencing the result. This is done by subtracting this result of the control (normal layer) with the result of the thick layer (that consist of lack of fusion and balling effects). Thereafter results should give an indication on possible identifiers for defects. The results are seen below in Figure 6.

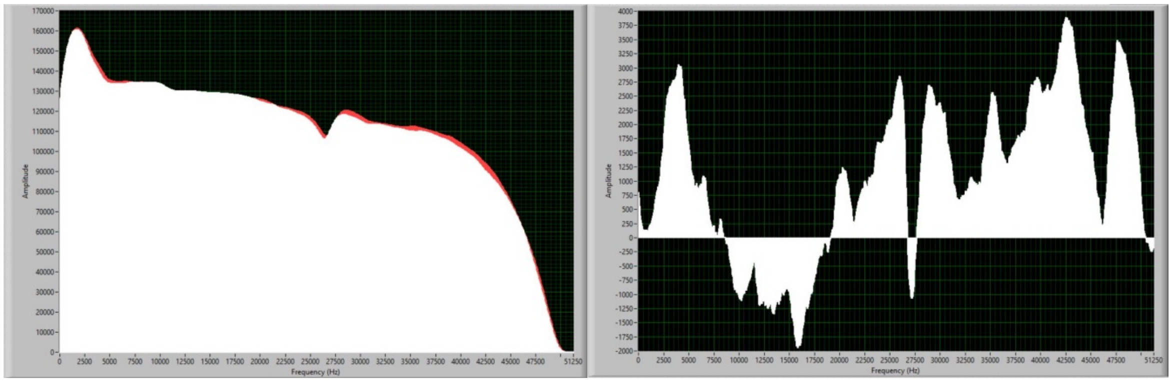

Figure 6: Energy content of optimal and non-optimal scanning over frequency range (left). The energy difference between optimal and non-optimal scanning (right)

In Figure 6, the y-axis indicates the magnitude and the x-axis indicates the different frequencies. The left graph shows the magnitude of the two different signals, white indicating the optimal tracks and red indicating the non-optimal tracks. The right graph shows the difference in the magnitude of the optimal and non-optimal signals. It can be seen that the results of the spectrogram in Figure 5 is more prominently shown in Figure 6. If there was no difference in the optimal vs non-optimal then the result in Figure 6 (right) would have been zero. This frequency graph shows large variances. The right side of Figure 6 shows that the large indicators are present in high frequency range. The differences can be used as an indicator for online detection of porosity forming phenomena during fusion or lack of fusion in metal laser powder bed fusion.

Conclusion

The purpose of this paper was to identify an online monitoring AE technique to determine lack of fusion of single tracks. Much research could still be done, for instance: identifying the minimum layer thickness for error detection using AE; ideal AE pre-filtering and the effect of different materials. The significance of this paper is indicators for online detection of porosity forming phenomena such as lack of fusion during metal LPBF. This study shows that STFT could be a valuable tool in the analysis of online detection of porosity forming phenomena during metal LPBF. An automated online process can be developed using these defect indicators. To conclude these nondestructive AE identifiers could be used to validate metal LPBF parts.

Acknowledgment

This work is based on the research supported by the South African Research Chairs Initiative of the Department of Science and Technology and National Research Foundation of South Africa (Grant №97994) and the Collaborative Program in Additive Manufacturing (Contract №CSIR-NLC-CPAM-15-MOA-CUT-01). The authors are grateful to IMCE for carrying out the impulse excitation measurements.

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