In situ process monitoring by optical microphone for crack detection in Laser Metal Deposition applications

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Abstract

We introduce an effective application of a novel laser-based optical microphone for in-situ monitoring of cracks during laser metal deposition (LMD) processes. The system relies on XARION's technology, a membrane-free optical microphone based on a Fabry–Pérot laser interferometer, that captures broadband airborne acoustic emission up to 1 MHz such as the sudden acoustic emission signals produced by the released energy of cracks. A set of experiments of two different applications, materials and geometries were conducted at AIMEN for evaluation: thin walls of stainless steel and thin deposited layers of tool steel. Through analyzing acoustic STFT-based spectrograms, an approach for identification of cracks and classification of signals is introduced. Process emission of 200 kHz and crack-type signals up to 600 kHz were detected for both cases. NDT methods (X-ray and Eddy Current) and microscopy investigation of defects validate this acoustic sensing system to monitor cracks in laser cladding and other additive manufacturing applications.

Keywords: sensing; monitoring; crack; cladding; additive.

1. Introduction

Laser metal deposition (LMD) processes are gaining growing interest by the industry as they are well suited to build large-sized components, even over non-flat surfaces and with high building rates (0.5-1Kg/h) compared to other additive manufacturing (AM) technologies. In LMD, metallic powders are blown through a deposition nozzle and molten with a laser to produce a metallic bead. Main applications of LMD are building new metal AM parts; reconstruction and repairing by adding up powders with identical or enhanced properties with respect to the base material, which improve part functionalities such as corrosion or wear resistance. In these processes, one of the most common defects that limit final part quality are cracks, as they can considerably reduce the mechanical strength of the component. Thus, the wider adoption of these technologies requires in-situ monitoring systems.

In previous studies based on acoustic emission monitoring [1][2][3][4] the main drawback identified is that conventional microphones are too sensitive to noise sources in the audible frequency range up to 20 kHz.

In this paper we leverage XARION´s novel, proprietary optical microphone technology [5] to detect crack formation in LMD in two different applications. Results with this acoustic sensor in laser welding [6][7] and laser cladding [8] demonstrated that also higher ultrasound frequencies can be accessed to evaluate the process condition and detect process deviations, free from interference of low-frequency disturbances. These previous works on acoustic emission provide references for different crack phenomena mechanisms and acoustic fingerprints [3],[8].

Stainless steel 316L (SS 316L) is characterized by its predominantly single-phase microstructure of austenite and its good weldability. Nevertheless, austenitic SS are also susceptible to hot cracking during welding depending on several factors such as chemical composition and solidification rate. Although LMD differs significantly from conventional welding, hot cracking can also occur because of similar reasons. Generally, these are associated with the solidification or reheating processes during AM. Main mechanisms of nucleation and propagation of cracks are solidification cracking and liquation cracking [9].

AISI M2 is a high-speed steel combining mechanical strength with a high wear resistance. It can reach a hardness of up to 62 HRc, when applied the suitable heat treatment, resulting in a complex martensite matrix with a dispersion of several carbides (MC, M2C, M6C, …) of the alloying elements (V, Mo, W) [10]. These properties make it very demanded for cold and hot working steel tools, like cutting tools, cold work rolls, high-speed machining tools, etc. and also very suitable for tool repairing or wear resistance coatings for these types of tools. One of the technologies used for tool repairing or applying coatings is LMD, which enables the production of homogeneous and defect-free layers on other tool materials (tool steels, cast irons) [11],[12],[13]. Nevertheless, cracks can occur if the processing parameters lead to a high accumulation of residual stresses [10],[14] and even lead to extensive microcrack formation in regions where carbon segregation takes place.

2. In situ acoustic monitoring technology in Laser Metal Deposition

The optical microphone is an air-coupled acoustic detector for sound pressure waves from 10 Hz to 2 MHz. It works on the principle of interferometry and consists of a control unit containing a laser which sends its light over an optical fiber to a sensor head. This sensor head, depicted in Fig.1, encapsulates of a pair of parallel, partially reflective mirrors, a so-called Fabry-Pérot etalon. A sound wave passing between the two mirrors causes small shifts in the wavelength of the laser light. This in turn affects the amount of reflected light coming back from the interferometer, which is turned into an electrical signal via a photodiode as described in more detail under references [4][5].

As the sensor dimensions are very small and the sensor head is fiber-coupled, it can easily be mounted in proximity to the LMD process (Fig. 1b). The model used in this set of experiments was XARION's Eta250 Ultra with a frequency range of 10 Hz – 2 MHz. To realize an in-situ monitoring system, the analog signal is fed into an Optimizer4D data acquisition system by QASS and digitized with 24 bit / 2 MHz. Simultaneously, a short-time Fourier transform (STFT) of recorded signal segments at a rate of about 32 000 spectra / s is performed. The resulting spectrogram is then used as a basis for the analysis (Fig. 1c).

For the applications under study, feedstock materials used are Stainless Steel 316L (SS316) and Tool Steel M2. Test coupons were manufactured with an LMD industrial workcell at AIMEN (Fig 1b). It includes a 6-axis industrial robot ABB4400 that is carrying the process head. Main process equipment is a thin disk laser TruDisk coupled via 200μm optical fiber to a Permanova process head WT03. A powder feeder from Medicoat delivers the metallic powder through a coaxial injection nozzle COAX8 from Fraunhofer IWS.

3. Experimental procedure

3.1. In situ sensing and data acquisition

Preliminary tests were carried out to find out the optimal sensor location, balancing signal-to-noise ratio and avoiding potential hits coming from blown powder particles bouncing off the base plate. Authors found out the optimal placement of the sensor to be at about 20 cm distance. (Fig. 1b) The dedicated acquisition and monitoring system calculates and also displays the spectrogram in real-time, whereas audible and low-frequency machine noise are filtered out using a high-pass filter of 40kHz. The signals observed during LMD are shown in Fig. 1c: General process signal detected mainly in frequencies below 200kHz, and cracks - emitting frequencies up to 600kHz - during and after the process.

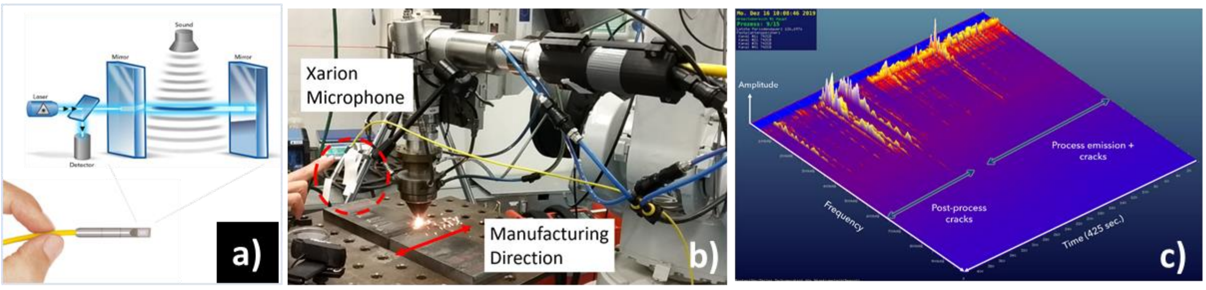

Fig. 1 (a) Optical microphone principle and size (b) LMD manufacturing and in-situ sensing system (c); Spectrogram representation as output from monitoring software containing both process and crack signals.

3.2. LMD process tests and NDT characterization

A set of experiments and dataset acquisitions of different applications and geometries were conducted. Those representative tests are: thin walls on stainless steel 316L (SS316) and thin coated layers of M2 high speed steel on tool steel (Tenasteel®) baseplates. The main process conditions are presented in Table 1.

Crack sensitivity was studied through established Non-Destructive Testing (NDT) techniques. X-ray radiography was used to analyze AM coupon tests (Experiments 1 and 2) and Eddy currents were used to analyze coated layers (Experiments 3 and 4). Further metallographic analysis was also carried out to support observations.

Table 1. Summary of process tests carried out corresponding to selected datasets

Experiment ID (Description of the specimen)	Materials	Laser Power (W)	Speed (mm/s)	Powder flow (g/min)
1 (20 layers, 2 tracks/layer)	SS316L	1000	10	8
2 (40 layers, 2 tracks/layer)	SS316L	1000	10	8
3 (1 layer, 9 overlapping tracks)	M2	1900	15	12
4 (1 layer, 9 overlapping tracks)	M2	1500	8	10

3.3. Crack counting in the acoustic signal

The automatic crack identification and count algorithm was implemented based on the following workflow: (1) raw acoustic signal; (2) spectrogram of the signal is calculated with a signal segment (bin size) of 128 samples and bin overlap of 16 samples; (3) Acoustic energy of the signal segment is calculated from the spectrogram, integrating the amplitude of each frequency component in different bands; (4) Threshold and spectral bands for crack detection are investigated by data analysis methods and selected afterwards as explained in section 4.2; (5) Peaks above these thresholds are counted as cracks [8].

4. Results

4.1. NDT and metallographic inspection

Results from X-ray radiography and Eddy Current for tests are shown in Fig. 2 Based on these NDT, we estimate by basic image processing and naked eye the number of large and visible cracks of each case (Table 2).

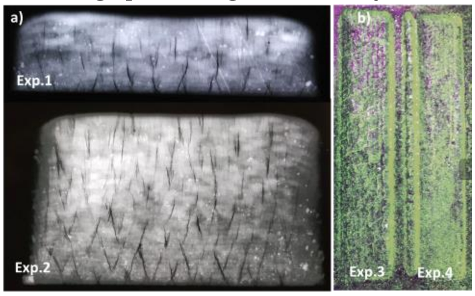

Fig. 2. Radiography and Eddy current inspection

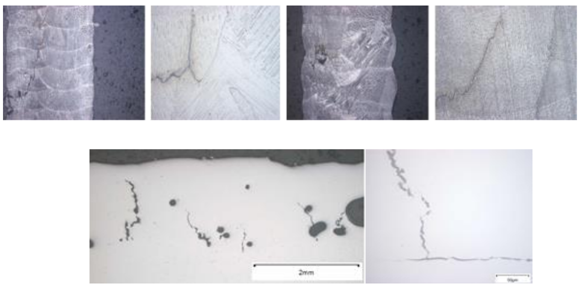

Fig. 3 Metallographic crack examination in SS316L (top) and M2(bottom)

Metallographic inspections of the crack geometries provide insights about defect mechanisms and its morphology. In the case of SS316L, they are characterized by an intergranular fracture surface and a cellular structure. In the case of M2 high speed steel, the metallographic inspection of cross sections of superficial cracks reveals that also smaller internal cracks are initiated in pores and inclusions due to residual stresses. The larger cracks propagate towards both the surface, as an open crack, and the base plate, running inside the coating in parallel to the interface with the base metal (Fig. 3).

4.2. Crack count from in situ monitoring

As shown in the spectrogram (Fig. 1c) several crack signals are easily distinguishable from the process signal due to their intensity. However, less severe cracks produce lower acoustic signals with an intensity close to the process' acoustic signal. Therefore, for the crack detection algorithm, it is important to select the right frequency range and threshold.

After data analysis, the optimal frequency range to detect crack signatures was identified in the band 350kHz-1MHz. The Z-scores of the acoustic energy in that band are then calculated, so each point of the signal is expressed as n times the mean deviation, which has been the procedure to select a common threshold after carrying out a threshold sweep for the datasets and analyzing the variation in crack count number. The optimal threshold for SS316L and M2 calculated were 9 and 35 times the standard deviation of the acoustic energy, respectively. The number of peaks above these threshold levels are then labelled as cracks.

Fig. 4 shows the acoustic energy in experiment 2 and 3. In blue the selected spectral band (350kHz-1MHz) and in green the complete signal. For SS316L, the signals associated to cracks are lower and cracks (highlighted with red dots) occurred during as well as after the process. Those are the main differences compared to M2.

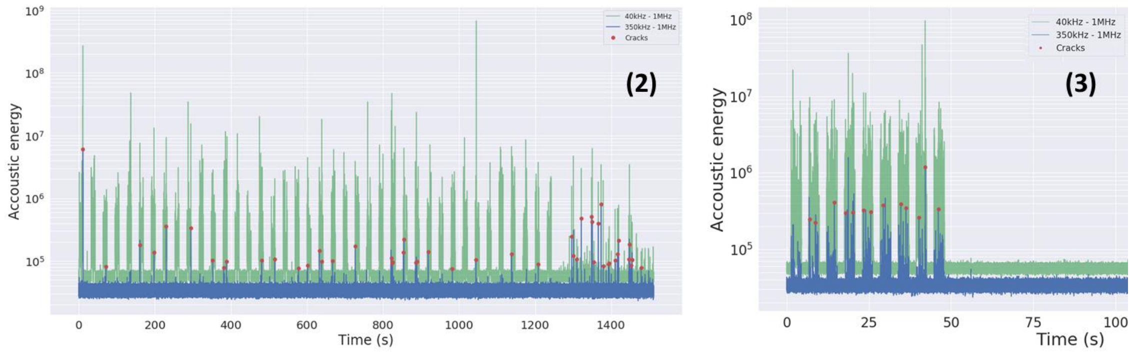

Fig. 4 Acoustic energy signal and peak detection using crack count algorithm (2) for experiment 2; (3) for experiment 3.

The resulting number of cracks counted using this method is summarized in Table 2. As shown, the number of crack counts by the automated method is correlated to the one obtained by manual offline NDT-based counting.

Table 2. Comparison between manual counting of cracks in X-Ray and Eddy Current images and automated counting (*1: Counting each line as one crack; *2: counting lines that intersect as one crack (these two methods provide indicative range of number of cracks)

Test ID (Total number of tracks x track length (mm))	Count from RX/EC *1	Count from RX/EC *2	Total automated count
1 (20 tracks x 50mm)	29	19	25
2 (40 tracks x 50mm)	50	37	49
3 (9 tracks x75mm)	12	11	13
4 (9 tracks x75mm)	6	4	7

5. Conclusions

In situ process monitoring using an optical microphone provides valuable information about the formation of cracks for laser cladding and additive manufacturing processes in a contact-free manner. Analysis of acoustic signals above 350 kHz has shown strong correlation in crack counts with offline NDT counting methods. As next steps, additional experimentation will provide reliability in the monitoring system and robustness of the detection method for these and other LMD applications. Further studies will be made to assess how certain parameter changes affect the crack appearance in order to intervene with those parameter in a closed-loop setup.

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