Effective Structural Health Monitoring with Additive Manufacturing

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EFFECTIVE STRUCTURAL HEALTH MONITORING WITH ADDITIVE MANUFACTURING

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ABSTRACT

The current remaining challenges for structural health monitoring (SHM) systems prevented the introduction of SHM systems on a large scale within industrial applications. An effective SHM system is required for the reduction of the direct operation costs, improvement of the life-safety and the introduction of additive manufactured components for critical structures. In this paper, a new structural health monitoring methodology will be presented for components that can be processed by additive manufacturing (AM) or 3D printing. The origin of the source concept will be explained together with the different possible configurations and the intrinsic strengths of the system. It will be concluded that these new AM production techniques and new SHM technique will allow the development of "intelligent" metal structures in the future. The importance of the SHM system for the breakthrough of the AM techniques will be highlighted for critical components such as primary aeronautical structures.

KEYWORDS : *structural health monitoring methodology, 3D printing, additive manufacturing, fatigue, intelligent structure*

INTRODUCTION

Additive manufacturing (AM), also known as 3D Printing or Rapid Manufacturing is a group of technologies used for manufacturing of (near)-net shape products (functional parts, prototypes, tooling components, etc.) starting from 3D computer-aided design (CAD) data or other geometry representations. These technologies are currently being explored and applied in numerous sectors such as aeronautical, space, automotive, energy, mechanical engineering and medical. Additive manufacturing is highlighted as the production technology of the future, enabling mass customization instead of mass production. Nowadays numerous types of metal alloys, polymers and ceramics can be processed with these new technologies. The additive processes were originally developed for the production of prototypes. However they show high potential for the production of functional, low volume, highly complex parts with high added value. Besides near-net shaped products these technologies can also be used for prototyping, feature addition, repairs [1] and coatings [1-2]. The Standard Terminology for Additive Manufacturing Technologies has been defined by the ASTM F42 and ISO TC 261 committee in the ASTM 2792-12a standard to clarify the plenitude of terms used by different organisations. This terminology will also further be used here. This standard also provides a categorization of the different types of AM technologies currently in use. In this paper, the focus will be on the metallic AM technologies that have a high potential to create structures with excellent material properties in the future.

One of these technologies is Layerwise Laser Melting (LLM), which is categorized in the Powder Bed Fusion techniques. Layerwise Laser Melting is often referred to as Selective Laser Melting (SLM) (MTT technologies), Laser Cusing (Concept Laser GmbH) and Direct Metal Laser Sintering (EOS). These terms refer to the same process. An overview of a typical Layerwise Laser

Melting process chain is illustrated in Figure 1. In this process the STL (STereoLithography) file format is generated by computer aided design (CAD) software or reverse engineering equipment. This STL file describes the external closed surfaces of the object. The STL format serves as the input for the slicing procedure in which the STL representation of the object is sliced in parts with a predefined thickness. These slices can be interpreted as 2D sections of the object that are used to generate the scanning pattern for each layer. In the LLM (or SLM) production process a thin layer of powder is deposited with a thickness equal to the slicing thickness initially onto the base plate and sequentially the powder is melted selectively according to a predefined scanning pattern, by means of a laser source [3]. Afterwards the building platform with base plate translates downwards with a distance equal to the thickness of one layer. Then a new powder layer is deposited and scanned. This sequence is repeated until a complete part has been built. Next the part is stress relieved and heat treated if required. Following the part is cut from the base plate and building supports are removed. As a last step the part can be machined and polished if necessary.

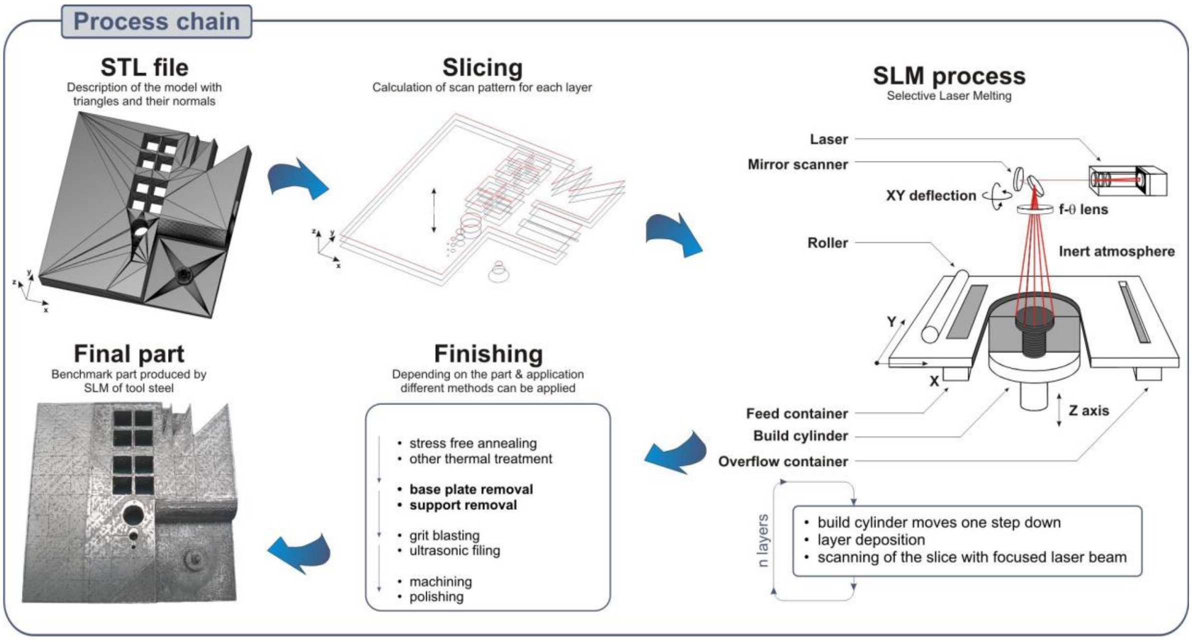

Figure 1: LLM process chain [3-4]

A second technology is Laser Metal Deposition (LMD), which is categorized in the Direct Energy Deposition techniques. Laser Metal Deposition is often referred to as Direct Metal Deposition (POM Group), Laser Engineered Net Shaping (Optomec) Laser Cladding or Construction Laser Additive Direct (BeAM), Beam Deposition (BD). These terms refer to the same process. A schematic representation of the LMD process is given by Figure 2. In this process a high-power laser beam is focused on the surface of a solid metallic workpiece, locally heating the material surface. The powder stream is preheated by passing through a focused laser beam. Subsequently the preheated metallic powder stream is blown into the laser-induced melt pool at the workpiece surface. The heated metallic powder is blown into this melt pool where it mixes with the molten substrate material. As the nozzle is moving, the melt pool solidifies and a track of solid material (a clad) is formed. By sequentially applying multiple clads 3D components can be produced. The workpiece can be a base plate as in the LLM process or a machined part produced with conventional production methods. The post processing steps after the LMD process are similar to the LLM process. The maximum deposition rate and track width currently reported in the literature are respectively 18kg/h of INCONEL 625 and 20mm. At the other side of the spectrum for high precision LMD components with feature dimensions below 100µm are possible [5].

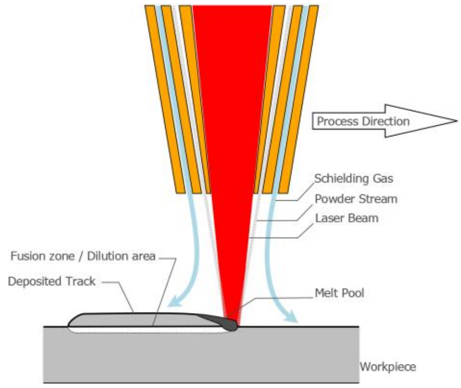

Figure 2: Schematic representation of a LLM machine

The paper starts by presenting fundamental challenges that exist in the development of Structural Health Monitoring (SHM) systems for industrial applications. These challenges formed the basis toward the effectiveness of the new SHM methodology that will be described in Section 2. In this Section the defect localisation capability of the system will be explained including its intrinsic positive characteristics. In Section 3 the initial demonstrators will be discussed. Final remarks, conclusions and future vision with respect to additive manufacturing and structural health monitoring are given in the last Section.

1 FUNDAMENTAL CHALLENGES FOR SHM

Structural Health Monitoring (SHM) is defined as “the process of acquiring and analysing data from on-board sensors to evaluate the health of a structure.” in the ARP 6461 standard issued by The Aerospace Industry Steering Committee on Structural Health Monitoring and Management (AISC-SHM) which operates as a Technical Committee with SAE Aerospace with in the Aerospcace Devision (G-11 SHM). Health is the ability to function/perform and maintain the structural integrity throughout the entire lifetime of the structure [6].

As stated by Prof. C.R. Farrar one of the most fundamental challenges is the fact that damage is typically a local phenomenon and may not significantly influence the lower-frequency global response of structures that is normally measured during system operation. Another fundamental challenge is to develop the capability to define the required sensing system properties before field deployment and if possible to demonstrate also that the sensor system itself will not be damaged when deployed in the field [7]. A self-test functionality should also be present within the SHM system that allows the user to verify the proper functioning of the system to eliminate the false detection potential.

According to the authors, another fundamental challenge exists within the definition of the lowest amount of parameters to be measured to reach the required system performance. This challenge can clearly be deduced from the fact that condition monitoring of rotating machinery, which is one of the only SHM systems that has been able to successfully make the transition from research to practice, has a clear benefit from the capability to define the condition of the machinery and required maintenance with a limited amount of installed sensors. In addition, it will be a clear benefit regarding the maintainability of the SHM system to have a small number of sensors. Also the SHM system reliability will be directly impacted by the required number of sensors. The effort to make the SHM more redundant and ‘fail-safe’ by equipping the structure with a backup sensor has a smaller economical consequence as well. Finally the minimisation of the required number of sensors will automatically lead to a reduction of the amount of data that needs to be transmitted, processed and stored. It can be concluded that the required number of sensors is a challenge with a high multiplication factor with respect to the acceptance potential of the SHM methodology.

The academic community has proposed numerous Structural Health Monitoring (SHM) techniques in the last decade [8-9]. Many of these approaches work well in laboratory conditions but are not sufficiently effective and robust to be applied in practice. Usually the test configuration retrieved in the test specimens investigated in the laboratory isn't representative to the complexity of real life structures e.g. multi-layered structures. The challenge for SHM systems will be to cope with the varying boundary conditions of complex structural configurations and remain effective in these conditions.

One aspect that is often overlooked is the lifetime of the monitoring system itself and its robustness with respect to the operational environmental conditions [10-11]. The importance of this robustness cannot be underestimated typically for the aeronautical industry. This was clearly indicated by the specification sheets that were set up within the European Research Projects AISHA I and AISHA II in which the Acoustics and Vibrations Research Group participated together with companies such as Airbus Helicopters and Lufthansa Technics. These specification sheets were summarising the operational and end-user requirements for metallic and composite primary structural aircraft components. It can be concluded that the durability, reliability and longevity in practice of SHM is a key challenge for the successful implementation of a SHM system in real life applications.

According to the authors this robustness request should also be translated in another core challenge for SHM systems namely the integration within the structure itself. Like this it can be damaged by accidental mechanical loads that are not problematic for the structure itself. Secondly when sensor data from the material is necessary embedding or integrating sensors will also be required [12].

Besides the technical challenges stated above there are also some challenges in other domains that currently block the introduction of SHM systems into industrial applications. The SHM system should be straightforward, user-friendly and interpretable by the maintenance personnel otherwise the system cannot be deployed on a large scale in industry. Structural owners will also need to be convinced of the cost benefit of using a SHM compared to the current typical maintenance approaches and procedures. Additionally regulatory bodies will need to be convinced of the significant life safety benefit of SHM system. The insurance organisations need to be demonstrated that there exist serious risk reduction opportunities with the introduction of SHM systems; this should also allow the manufacturing industry to introduce more efficiently new innovation on different levels. Another significant challenge that could arise in a number of cases is the fact that the business models of the manufacturing industry could need to be completely changed in order to introduce a SHM system in a profitable manner. The company will may have to change from solely being active in the secondary sector of the economy and selling their product to their clients towards the tertiary sector of the economy and offering a service to their clients.

Finally another fundamental challenge is the cost of the SHM system itself and the installation cost. A large scale implementation of a SHM system would be inhibited if the cost is not acceptable in a large number of applications. This would form a serious limitation to introduction of SHM systems [13]. The cost should be as low as possible; to achieve this goal an automated production process and installation will definitely form a crucial factor together with the required number of sensors. This automation request will probably require new production technologies such as additive manufacturing.

2 METHODOLOGY

The Acoustics and Vibration Research Group (AVRG) at Vrije Universiteit Brussel has developed a new SHM methodology. A SHM system that conforms to the specified methodology is called an effective Structural Health Monitoring (eSHM) system. The objective during the development was to tackle in the largest possible extent the previously mentioned fundamental challenges and the pursued requirements of the specification sheets by the intrinsic capabilities of the new eSHM system. Our previous research has indicated that the harsh environmental conditions and geometrical varying boundary conditions together with the other operating requirements are real stumbling blocks for the practical implementation of a SHM system and lead to the conclusion that a future SHM system has to be robust, straightforward, cost effective and able to deliver the requested detection capacity and reliability level needed by the industry.

The eSHM system embraces the new design freedom offered by additive manufacturing technologies. These techniques offer a huge freedom with respect to the definition of the internal topology of structural components and allow producing bionic components. This design freedom enabled the introduction of 3D networks of capillaries or cavities within the structural components. These integrated capillaries within the structure connected to a pressure sensor mimic a nerve cell of living creatures but with the peculiar characteristic of a nociceptor with a variable receptor position along the nerve cell.

The measured physical quantity of the proposed eSHM system is the absolute fluid pressure in a closed 3D-curved network of capillaries that are integrated with AM techniques in the structural component or added on top of them. The capillaries are typically filled with a fluid such as a noble gas or a liquid penetrant or a mixture of both. This results in a SHM system that can be implemented for online/offline direct monitoring of structural components for the detection and localisation of cracks or extensive wear phenomena in structural components. The operating principle for the detection of a crack or extensive wear is straightforward: when a crack or a wear phenomenon penetrates the capillary or cavity a leak flow will occur and the internal absolute pressure will drop or increase depending on the pressure difference between the internal pressure inside the capillary and the external environment. For the detection a pressure sensor with a limited frequency range and sample rate is sufficient to detect the crack or wear.

An illustrative example of a component with a capillary system on top of a structure which was produced with conventional production methods can be retrieved in Figure 3(a). In this example the grey block was produced with conventional production methods and the red part was added by an AM technique. The blue capillary could directly be produced within the AM process itself or could be an existing component. In the latter case the AM techniques would be used to combine two conventional manufactured components. The LMD technique is suited for these applications due to the fact that it does not require a flat substrate surface to start from. This illustrates that the eSHM system does not require the component to be manufactured completely with AM techniques and is an important asset with respect to economic feasibility of the eSHM system. In this manner the LMD process is only used to create added value with a limited added volume amount. Figure 3(b) illustrates the possibility to integrate the capillary system within the original dimensions of the structure if this would be necessary from a functional point of view.

(a) (b)

Figure 3: eSHM system for conventional manufactured structure (a) outside original dimensions (b) inside original dimensions

When the structural component fits within the typical building volume of 250x250x250mm of the LLM machine and the component needs to be produced completely with AM techniques the capillary or cavity network could be added without any real cost impact with respect to the production cost of the component. The LLM has clearly some advantage compared to other AM techniques with respect to the geometrical accuracy. Therefore capillaries can be produced with a higher dimensional accuracy. An illustration is depicted in Figure 4 that shows a gear with integrated capillaries shown in red.

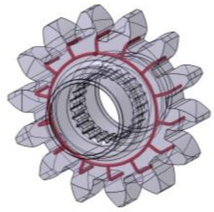

Figure 4: Illustration eSHM methodology in a cogwheel

In Figure 4 the integrated capillary is indicated in red. It can be noticed that the sections of the gear teeth with the maximum bending moment have received a capillary to monitor cracks that could exist within these sections. The stress engineer will need to take into account the implementation in the static stress calculations but due to the fact that fatigue initiation and the initiation of extensive wear phenomena are surface related phenomena [14] they should not be impacted by internal structures when these are properly designed. For fatigue applications the first capillary structure can function as the detectable limit and a secondary separated internal capillary network structure can function as an indication of reaching the critical crack length. These are also the key crack lengths which are used in damage tolerance fatigue calculation philosophies. Typically a safe operation is guaranteed by requiring a minimum number of cycles between these two crack lengths which is also directly linked with the inspection intervals. In this manner the eSHM system can be integrated in the current development process of damage tolerance designed structures without having a large impact on the design process itself.

The operating principle for the localisation of a crack or extensive wear for the eSHM system is based on the time of flight principle. The time difference between the arrivals of the pressure change due to the leak at the two sensor positions enables the system to localise the penetration point within the capillary. Figure 4 provides a schematic overview of the working principle for the localisation of the cracks or extensive wear. As illustrated in the figure, the two sensors will observe the pressure waves (the red pressure wave moves to the left and the blue pressure wave moves to the right) at a different moment in time due to the different distances between the crack position and the position of the two pressure sensors.

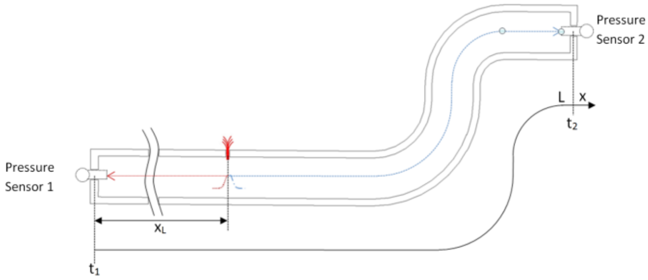

Figure 5: Schematic overview localisation working principle

The pressure change in the capillary travels at the speed of sound through the capillaries so that a measurement system with a high sampling rate is required. The speed of sound varies mainly with the temperature so the measurement of the temperature will also be required. If the pressure change travels at a temperature of 20°C in air a theoretical measurement localisation accuracy of 3,4mm should be reached if a sample rate of 100 kHz is used.

To finalize this section of the methodology some of the key assets of the eSHM system will be highlighted. Larger zones of complete structural components can be monitored with one sensor. As highlighted in the section about the main challenges this has a serious multiplication factor. The system itself is robust with respect to environmental conditions and changing geometries. The sensor can be a robust, reliable and maintainable pressure sensor. It can be installed on a location which is easy to maintain without provoking disassembly costs. There is an embedded physical memory in the system which enables the transmission of a small amount of data to a centralised processor. This also offers the possibility to do online or offline monitoring. The data itself is very straightforward to interpret by the system and maintenance personnel. The system has a cost-conscious profile for components that are produced completely with AM techniques.

3 FEASIBILITY DEMONSTRATORS

Currently the research efforts for the development of the eSHM systems are focussed on metallic components but the system could also be integrated in polymer parts, hybrid components such as metal matrix components etc. Currently we are able to produce capillaries with a minimum diameter of 1000μm for the LMD process and 500μm for the LLM process. To prove the feasibility of the eSHM systems four-point bending test specimens with an integrated eSHM system have been produced with LLM and LMD processes for two materials AISI 316L and Ti6Al4V. The 3D schematic representation of the four point bending test specimens is presented in Figure 6 (a) in which the internal capillary is indicated in red. In Figure 6 (b) a metallic test specimen is depicted with a pressure sensor installed on the left side and a check valve with mechanical stop on the right side.

(a) (b)

Figure 2: (a) 3D Schematic representation of feasibility test samples (b) Four-point bending feasibility test sample with installed pressure sensor

The detailed discussion of the results of these specimens does not fit in the scope of this paper but will be treated in subsequent papers. It can be stated that the initial results are very promising and positive.

CONCLUSION AND FUTURE VISION

It has been indicated that the eSHM system has the intrinsic potential for certain applications to meet a lot of the remaining fundamental challenges that have blocked the introduction of a SHM system within an industrial context. Of course further research will be required to optimize the system with respect to detection capability performance, demonstration of its robustness and effectiveness. Also the full capabilities of the AM techniques still have to be further exploited. This will certainly be the case once AM techniques will be combined with subtractive techniques which will allow the production of components on a μm scale and create “intelligent” metal structures in the future.

Metallic AM is a very interesting technology for the future production of lightweight intelligent structures with integrated functions. Weight reductions of 50% are not uncommon for the current demonstrators and this without decrease of the actual strength of the component. Another main benefit is the fact that the lighter a component becomes the cheaper the production price is for AM products, which is typically the opposite for the conventional production methods.

Currently controllability and consistency issues are some of the main blocking points for the introduction of AM techniques in industries with high fatigue requirements and low volume production. The integration of an eSHM system can significantly reduce the introduction risks and mean a breakthrough for these technologies. This has also been noticed as a major impediment with the introduction of composite components within the civil aeronautical industry. Besides the structures produced completely with AM, the small volume amount required for the production of the eSHM system opens the gate to higher production volumes of components manufactured with a combination of AM and conventional subtractive manufacturing and the creation of SHM systems for these applications.

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