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Acoustic emission monitoring of crack propagation in additively manufactured and conventional titanium components

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ABSTRACT

Additive manufacturing (AM) is a novel and innovative production technology that can produce complex and lightweight engineering products. In AM components, as in all engineering materials, fatigue is considered as one of the principle causes of unexpected failure. In order to detect, localise and characterise cracks in various material components and metals, acoustic emission (AE) is used as a non-destructive monitoring technique. One of the main advantages of AE is that it can be also used for dynamic damage characterisation and specifically for crack propagation monitoring. In this research, we use AE to monitor the fatigue crack growth behaviour of Ti6Al4V components under four-point bending. The samples were produced by means of AM as well as conventional material. Notched and unnotched specimens were investigated with respect to the crack severity and crack detection using AE. The main AE signal parameters –such as cumulative events, hits, duration, average frequency and rise time– were evaluated and indicate sensitivity to damage propagation in order to lead to a warning against the final fracture occurrence. This is the first time that AE is applied in AM components under fatigue.

1. Introduction

Over the last decades, the need for smarter and lighter materials is growing continuously. Indeed, in addition to the material strength, other characteristics were envisaged as well [1]. For example, the demands of the aerospace industry require lighter structures and materials that could operate at higher temperatures. In that aspect, light-weight materials with high strength performance and excellent corrosion resistance –such as titanium alloys– are deemed to be suitable. Lately, additive manufacturing (AM) has considerable interest both in academia and industry [2,3]. The recent developments in the AM technologies have enabled the production of complex and lightweight metallic structures while it is proven that the material effectiveness of AM is much higher compared to traditional manufacturing processes. Two of the main AM processes for the production of the metallic parts are the selective laser melting (SLM) process and the laser metal deposition (LMD) process. The SLM method is a powder bed fusion method while the LMD method is classified in ISO/ASTM 52900 as "direct energy deposition" [4]. LMD is a direct additive manufacturing technology and can also be called laser engineered net shaping (LENS), laser cladding (LC), etc. [5].

The additively manufactured structures are among others successful candidates for aeronautical applications [6]. However, due to the nature of these applications, those high-quality materials and their properties should be well understood. During the AM process, high thermal gradients cannot be avoided. Consequently, internal stresses [7], unique microstructure [8] and internal defects [9] can compromise their mechanical response –such as the fatigue life. Fatigue is considered as one of the main damage phenomena in metallic structures in aerospace [10]. The fatigue life of a component that is subjected to continuous cyclic loading, can be separated into three stages. The first stage is the stage where a crack nucleates and at the second stage the crack propagates. At the third stage, the crack is reaching the critical length where the final failure of the component occurs.

Non-destructive techniques (NDT) can be used to detect cracks. For example, eddy current inspection, liquid penetrant inspection, and ultrasonics are methods that can be used in order to detect macro-defects of certain sizes [11]. Another technique is acoustic emission (AE) and as a method is widely used for damage identification. Furthermore, based on the AE signal analysis, the AE can provide information on critical aspects such as the cracking mode [12] or the onset of a crack as demonstrated in [13]. On the other hand, AE can also be used as a dynamic damage detection method in

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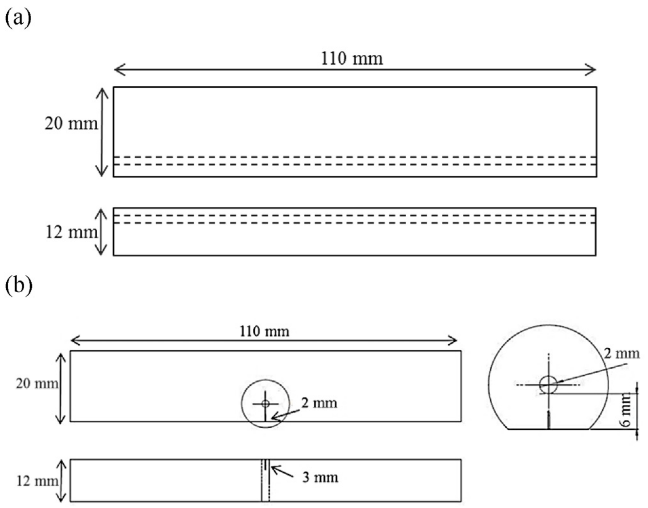

Fig. 1. Geometry of the specimens used for acoustic emission monitoring (a) unnotched LMD specimens; (b) notched conventional specimen and notched laser metal deposited (LMD) specimen.

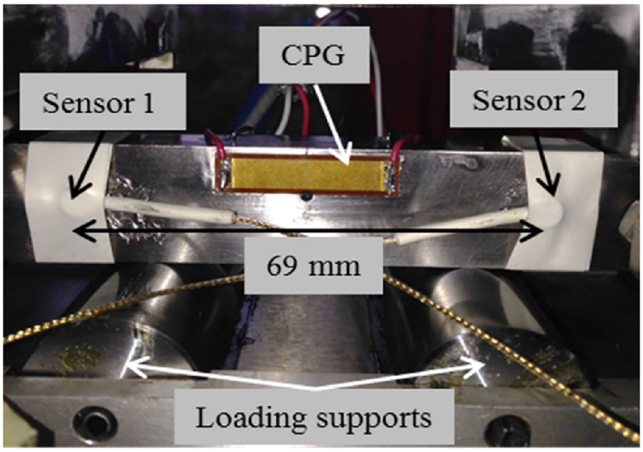

Fig. 2. Experimental setup of the notched sample with acoustic emission sensors.

the aspect of damage characterisation and crack propagation monitoring [14–16]. When a crack nucleates or propagates, energy is released by the source of the crack. AE transitory elastic waves are propagating within the material and are detected by piezoelectric sensors that are attached to the surface of the material [17,18]. The crack propagation is the source of the AE, and as a result, the progressive AE behaviour is associated with the severity of the damage. Additional to the number of the cumulative AE signals, the location of the damage can be also determined by the time delay of the transient elastic wave between the different sensor positions [19]. Furthermore, important signal measurement parameters such as the amplitude of the waveforms, the energy of the elastic waves, the rise time (RT) or the duration of the AE signal are regarded as essential inputs to the AE analysis concerning the damage accumulation.

In this study, we use Ti6Al4V four-point-bending specimens to investigate the AE behaviour during the propagation of fatigue cracks. Mill-annealed and additively manufactured titanium samples are subjected to fatigue in notched and unnotched specifications. Concurrently, AE sensors are monitoring the crack growth behaviour of the samples to correlate the AE parameters with the crack growth rates that are revealed from the installed crack propagation gauges. It is shown that the AE signal parameters are highly affected by the crack propagation in AM and conventional specimens and they can be used in order to identify the severity of a crack.

2. Experimental setup

2.1. Materials and fatigue testing procedure

During this investigation, a limited number of samples was available. Three specimens were used in order to monitor the crack propagation by means of AE. Two AM Ti6Al4V specimens produced by LMD process and one conventional mill-annealed Ti6Al4V specimen. The geometrical details of the notched and unnotched specimens are indicated in Fig. 1. In the first sample, the fatigue crack growth was investigated in centrally corner notched conventional specimen with a perpendicular capillary of 2 mm diameter (Fig. 1b). The second specimen was centrally corner notched LMD specimen, with similar specification as in first specimen. For the third sample, the fatigue crack growth was investigated in an unnotched LMD specimen with a longitudinal capillary of 1.8 mm diameter (Fig. 1a). The capillaries in both samples were used to study the effective structural health monitoring (eSHM) system. The eSHM system uses an integrated system of capillaries in order to detect cracks. This study mainly presents the AE behaviour during the crack propagation test, more details on the eSHM system can be found elsewhere [9,20,21].

The LMD specimens were produced by Vlaamse Instelling Voor Technologisch Onderzoek (VITO), a European independent research and technology organisation. In AM components, the crack growth behaviour can be affected by residual stresses. After the production of the specimens, a stress relief heat treatment was applied for 2 h. The current heat treatment was used to obtain stress-relieved conditions without changing the microstructural state of the samples. The specimens were heat treated in a horizontal tube furnace at 530 °C in argon atmosphere for 2 h with furnace cooling. The current furnace had two installed thermocouples inside and outside the tube that provide uniform and controlled temperature. The parts were machined to the final dimensions after the heat treatment. The corner notch was located at the centreline of the notched specimens and was applied using electric discharge machining (EDM).

For the testing of the specimens a four-point bending test was selected. Currently, there are not that many studies in the literature that investigate the four-point bending behaviour of AM samples. The current setup produces a tensile and a compressive region. The capillaries are placed on the tensile region of the setup where we expect to have the higher stress concentrations. The fatigue test experiments carried out on an MTS machine with a maximum load capability of 100 kN. During the test, a sinusoidal cyclic loading was applied with constant amplitude for each load level. The stress ratio was 0.1, and the frequency was selected to be 15 Hz.

The two notched specimens were initially subjected to the load level of 17.8 kN. After the crack initiation, the load amplitude was progressively lowered to achieve a smooth crack opening behaviour. For the case of the unnotched LMD specimen, the crack growth behaviour was examined at the load level of 37.3 kN. This load level corresponds to the load level at which the eSHM system detected a crack of 1.3 mm length after 254,958 cycles. For all the cases, the crack was monitored using crack propagation gauges (CPG) in order to report the crack length versus the fatigue life. The experimental setup is shown in Fig. 2.

2.2. Acoustic emission

Two AE broadband sensors "pico" type of Mistras Holdings were attached to the side of the specimen. The sensors had a broadband