

Embedded Structural Health Monitoring with Additive Manufacturing:  
post processes to improve fatigue properties

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## Introduction

Despite the interest of the aeronautical industry, the wide variety of AM process parameters and the inconsistency of the material properties limit the current applicability of the technology to non-safety critical applications. At the Vrije Universiteit Brussel, a novel concept of Structural Health Monitoring (SHM) has been proposed, particularly suitable for the monitoring of fatigue damage in Additively Manufactured (AM) components. This system is called the “effective Structural Health Monitoring” (eSHM) system. The system is essentially based on the integration of capillaries in the proximity of the expected crack growth path and the continuous monitoring of the pressure inside those capillaries. The capillary is initially pressurized at a pressure level different from the ambient conditions in which the component will operate. The fatigue crack will breach through the capillary and creates a leak flow that alters the capillary pressure. This is the indication of the presence of fatigue damage in the structure.

The current work explores the effect of post-processes on the fatigue performance of Ti-6Al-4V specimens with an embedded SHM sensor to detect fatigue damage. Because of the importance of thermal stresses, internal porosities and capillary surface roughness on the fatigue performance of such specimens, this manuscript evaluates the effect of a Stress-Relief (SR), Hot-Isostatic-Pressing (HIP) and Chemical Etching on the fatigue strength

## Test procedure

Four point bending test specimens were produced using laser based Powder Bed Fusion (PBF) technology. The capillary of the eSHM system is integrated in the tensile stressed region of the specimen in order to detect the fatigue damage early on. The dimensions of the test specimens are provided in Figure 1. The step method, as also used in this manuscript, is find a suitable and fast approach to determine the fatigue strength of Ti-6Al-4V specimens. According to this step method, the specimen is initially subjected to a load level below the expected fatigue strength of the specimen for a predefined number of cycles (run-out: 500.000 cycles). Beyond this number of cycles, it is assumed that fatigue fracture will not occur at this load level and the load level is then increased. This procedure continues till fracture occurs or the eSHM detected the fatigue crack. The eSHM system considers crack detection when the pressure level inside the capillary reached the pre-set limit of 0.85 bar.

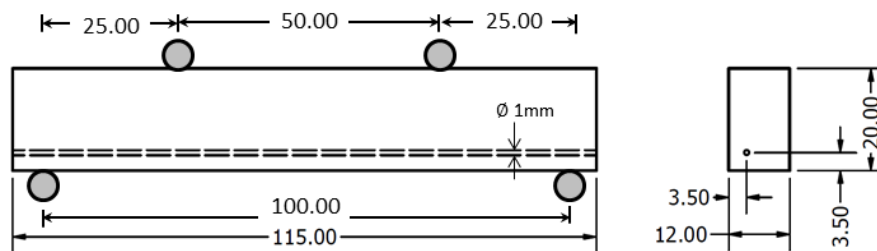


Figure 1. Ti-6Al-4V specimens inside a four-point bending fatigue test setup. Dimensions are in [mm].

## Results

The eSHM system successfully detected the fatigue cracks before final fracture for all tested specimens. Figure 2 presents the last second of the pressure recording of the eSHM system in three different specimens.

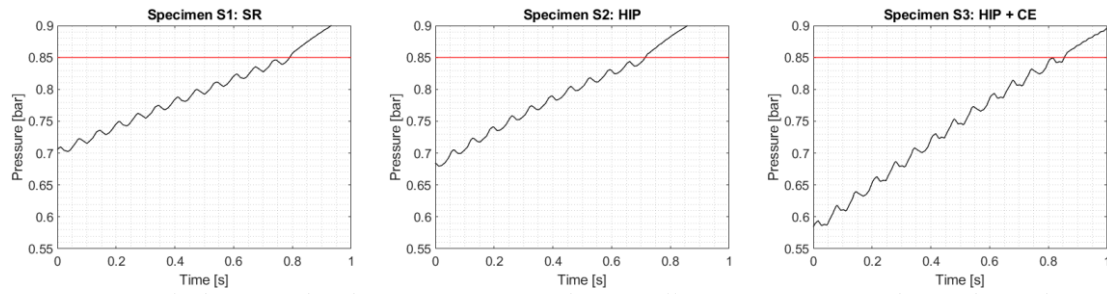


Figure2: Crack detection by the eSHM system when capillary pressure exceeds 0.85bar. The figure depicts the last second of the pressure recording inside the capillary of (a) Specimen 1 (SR) (b) Specimen 2 (HIP) and (c) Specimen 3 (HIP + CE).

The fatigue tests results are summarized in Table1. The fatigue performance of the Ti-6Al-4V specimens with different post processes largely varied. Specimen 1 (SR) failed at a stress level of 600 MPa due to a subsurface defect. The hot isostatic pressed specimen (Specimen 2) outperformed the stress relieved specimen and only failed at a stress level of 818 MPa. As concluded from the fracture analysis, fatigue initiation occurred at the capillary surface which is likely related to the higher surface roughness of this as printed surface. Since it is undesired that the integrated eSHM system causes fatigue initiation, Specimen 3 was post processed using both a HIP and CE procedure in order to reduce the capillary surface roughness. The improvement of the capillary surface roughness can be seen in Figure3. This surface roughness reduction resulted in a further increase of the fatigue strength (1130 MPa), a stress level at which a substantial portion of the test specimen has already been plastically deformed. Fatigue initiation did not occur on the capillary surface, but on the external surface of the four-point bending specimen. The eSHM system can be integrated inside Ti-6Al-4V without having an impact on the fatigue properties of the test specimen.

Table 1. Fatigue test results of Ti-6Al-4V specimens produced using Powder Bed Fusion (PBF) and different post processes.

	Post-process	Initial step [MPa]	Steps [-]	Failure step [MPa]	Cycles failure step [-]
1	SR	200	6	600	288 181
2	HIP	110	9	818	199 195
3	HIP + CE	110	13	1130	478 150

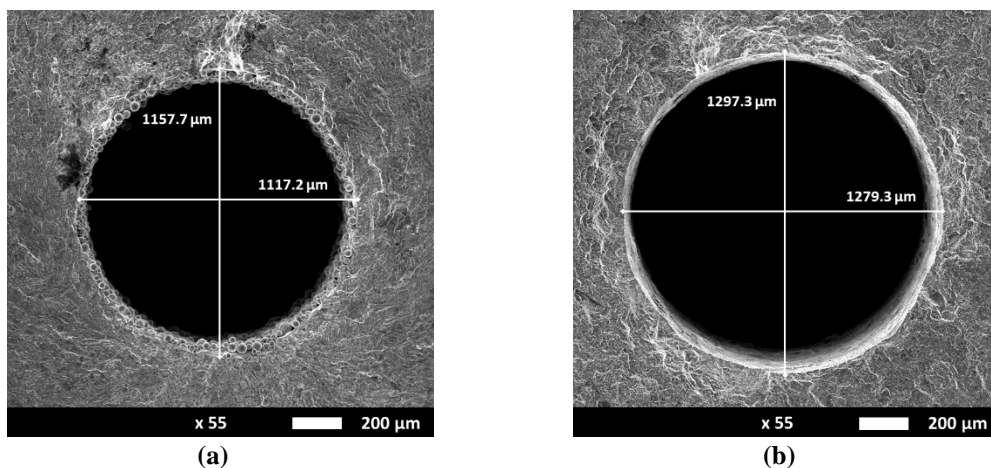


Figure3: Fractographic analysis is based on Scanning Electron Microscope (SEM) images of the fracture Surface. (a) Specimen 2: The surface roughness on the capillary initiated fatigue. (b) The capillary surface roughness has been reduced by the CE process.