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Fatigue performance of powder bed fused Ti-6Al-4V component with integrated chemically etched capillary for structural health monitoring application†

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Abstract: Fatigue performance of additively manufactured (AM) components is still uncertain and inconsistent. Structural health monitoring (SHM) systems offer a solution to continuously monitor the structural integrity of a structure. The effective Structural Health Monitoring (eSHM) system is the first SHM principle developed with the principal purpose to monitor AM components. The eSHM principle exploits the design freedom offered by AM to integrate a capillary inside the component. The capillary is put under low vacuum and the pressure is monitored during the operation of the component. As-built AM surfaces report elevated surface roughness and are one of the principle causes of premature fatigue initiation and fatigue failure. The current study will investigate the effect of a chemical etching (CE) post-process on the capillary surface and evaluate its effect on the fatigue performance.

Keywords: Structural Health Monitoring, Additive Manufacturing, Surface Roughness, Chemical Etching

1. Introduction

Additive manufacturing (AM) technologies are widely studied nowadays as they enable the production of complex shaped components with integrated functionalities. The applications of metal AM components in the industry is rising, but the remaining uncertainty on the fatigue behavior of metal AM components remains critical for industrial wide adoption. The so-called Structural Health Monitoring (SHM) systems offer a solution since their continuous monitoring allows capturing growing fatigue damage while in service. To maximize robustness and reduce the impact of environmental influences, an SHM system benefits from being fully integrated inside the component.

At the Vrije Universiteit Brussel, researchers have developed the "effective Structural Health Monitoring" (eSHM) system [1,2]. Using AM technologies, capillaries are integrated at the locations where fatigue cracks are expected to grow. Prior to testing, the capillaries are put under low vacuum and the pressure inside the capillary is continuously monitored during operation. The growing fatigue crack will breach through the capillary and induce a leakage. The resulting pressure change inside the capillary is a clear indication of the presence of a fatigue crack. With over 40 fatigue tests conducted, the eSHM has always successfully detected the fatigue cracks prior to complete fracture. Strantza *et al.* [3] presented that the eSHM system has reached TRL level 3. The capillaries of the eSHM system were produced either using laser based Directed Energy Deposition (DED) [4,5] or laser based Powder Bed Fusion (PBF) [6].

The work of Strantza *et al.* [6] presented the fatigue failure and fatigue crack detection by the eSHM system for as-built and stress-relieved specimens produced by laser based PBF. With the stress relieved specimen having a higher fatigue strength, residual stresses had proven to be the principal cause of early fatigue failure. Fatigue initiation occurred at internal porosities and at the capillary surface. This work therefore extents the latter work towards Hot Isostatic Pressed (HIPped) specimens to reduce internal porosities and residual stresses. To prevent fatigue initiation at the capillary surface, chemical etching (CE) will furthermore be used to reduce the capillary surface roughness. Fatigue strength and fatigue initiation location will be evaluated and fatigue crack detection by the eSHM system will be presented.

2. Materials and Methods

Two Ti-6Al-4V specimens were produced using laser based PBF with a layer thickness of 30 µm. After production, both specimens were HIPped and one of the specimens (Specimen 2) was chemically etched. The outer surfaces were then milled according to the design presented in Figure 1. The integrated capillary has a diameter of 1mm and its center is located at 3.5 mm from the side and bottom of the rectangular beam.

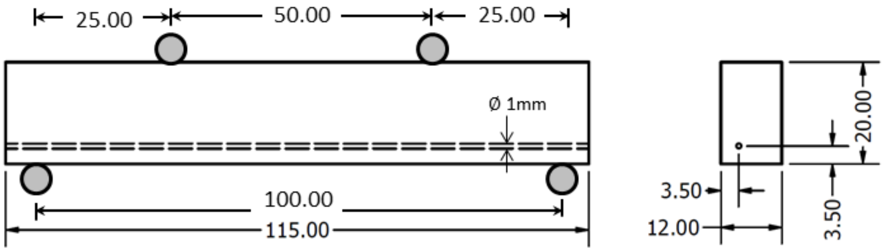


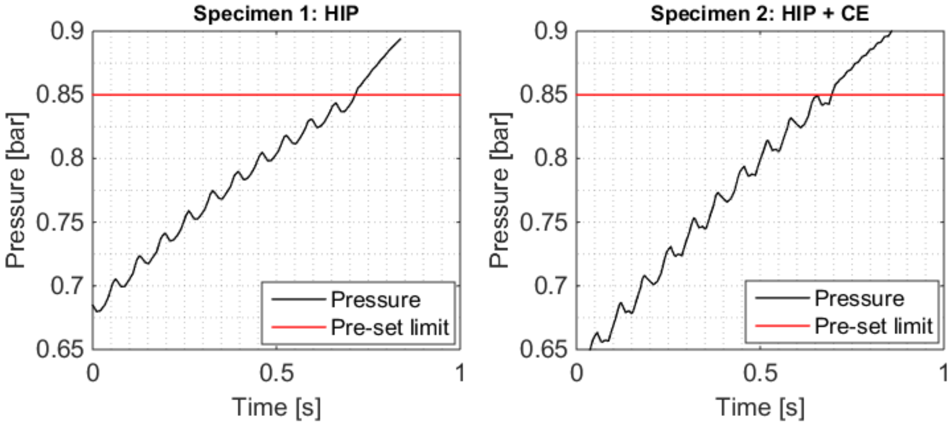
Figure 1. Ti-6Al-4V specimens inside a four-point bending fatigue test setup. Dimensions are in [mm].

To one end of the capillary a pressure sensor Kulite XTL-123BEG-190M-1.7 bar (Kulite Semiconductor Products Inc., Leonia, NJ, United States) was installed. A Clippard MCV-1-M5 check valve (Clippard Instrument Laboratory Inc., Cincinnati, OH, United States) was installed at the other end of the capillary. To properly seal the connections, a Loctite 577 thread sealant (Henkel, Düsseldorf, Germany) was applied to the M5 threads. The specimen with pressure sensor and check valve was put in a vacuum oven and capillary pressure was lowered to 0.1bar absolute. The test specimen was then placed in the four-point bending test setup in such a way that the capillary is located closest to the location of maximum tensile stress to detect growing fatigue cracks sooner. The step method was used to accelerate testing, with a run-out 500,000cycles in each step. The initial stress level was 114MPa, well below the expected fatigue strength [5,6], and increased with 78.1MPa in each step. The test frequency was 15 Hz and a stress ratio (R ratio) of 0.1 was used.

3. Results

3.1 Fatigue crack detection by the eSHM system

A fatigue crack is considered detected by the eSHM system when the pressure level inside the capillary exceeds a preset limit, here chosen to be 0.85bar. In both specimens, the eSHM successfully detected the fatigue crack before final fracture of the specimen. The last second of the pressure recording inside the capillary is depicted in Figure 2. The pressure rise in specimen 2 (HIP+CE) is slightly larger indicating that the fatigue crack is larger at crack detection.



(a) **(b)**

Figure 2. 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 (HIP) and **(b)** Specimen 2 (HIP + CE).

3.2 Fatigue failure and fracture surface analysis

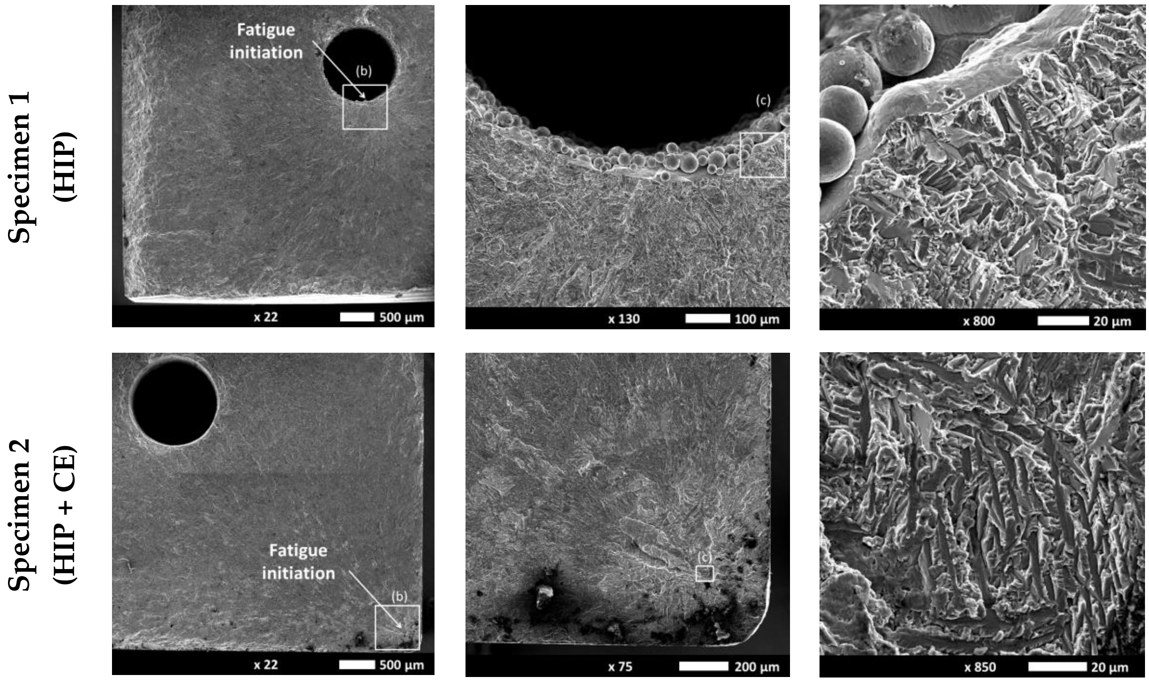
A summary of the test results can be found in Table 1. Fatigue failure occurred at a load level of 818MPa in the HIPped specimen without chemical etching (Specimen 1). As compared to previous tests, this result equals the benchmark of wrought Ti-6Al-4V specimens [5,6] as well as the stress relieved specimen produced using laser based PBF [6] and clearly outperforms all specimens tested under as-built conditions [6]. It is clear that HIP has certainly improved the fatigue performance, but fatigue initiation eventually occurred at the capillary surface. The capillary surface roughness now becomes critical.

To reduce the effect of the capillary surface roughness as a fatigue initiator, a chemical etching process was performed on a second specimen. Figure 4 clearly shows the impact of the chemical etching process on the capillary. As compared to the condition without chemical etching (a), the unmolten metal powder particles on the capillary surface have disappeared (b) and capillary surface roughness was reduced. Furthermore, the diameter of the capillary after chemical etching became larger by about 150μm.

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	HIP	110	9	818	199 195
2	HIP + CE	110	13	1130	478 150

Specimen 2 failed only at a load level of 1130MPa and outperformed Specimen 1 in terms of fatigue strength. Fatigue initiation did not occur on the capillary surface, but subsurface close to the bottom right corner in Figure 3 (c). Chemical etching has reduced the capillary surface roughness which resulted in the fact that the fatigue crack did not initiate at the capillary surface.



(a) **(b)** **(c)**

Figure 3. Fracture analysis of Specimen 1 (HIP) and Specimen 2 (HIP + CE). Specimen1: the fatigue crack initiated at the capillary surface due to the as-built capillary surface roughness. Specimen 2: the fatigue crack initiated subsurface near the bottom right corner. The fracture surface of both specimens (depicted in column (c)) shows the presence of facets, a clear indication for the fatigue initiation phase.

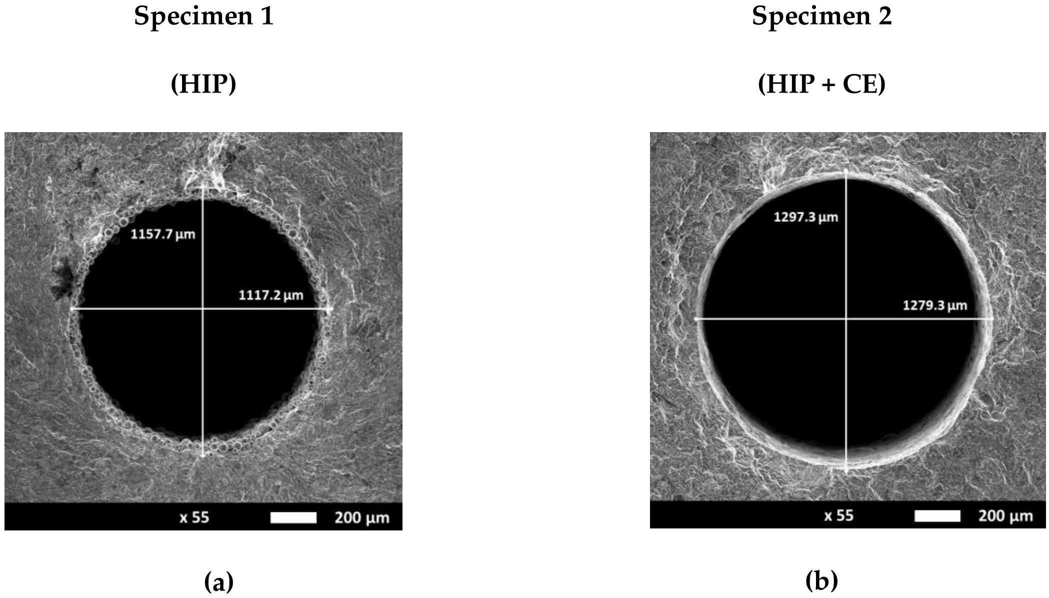


Figure 4. Capillary cross section of **(a)** Specimen 1 without Chemical Etching and **(b)** Specimen 2 with Chemical Etching. Chemical Etching reduced capillary surface roughness, removed unmolten metal powder particles and enlarged the capillary diameter by about 150µm.

4. Conclusion

Two Ti-6Al-4V fatigue test specimens were produced using laser based Powder Bed Fusion. The capillary of the eSHM system was integrated during the manufacturing process and put under low vacuum prior to testing. With the fatigue cracks eventually breaching through the capillary and inducing a leakage, the eSHM system successfully detected the fatigue crack in both specimens prior to final fracture.

Both specimens were HIPped to limit the impact of residual stress and porosities on the fatigue strength of the test specimen, as concluded from a previous test campaign [6]. Both HIPped specimens had higher fatigue strengths than the specimens tested under as-built conditions. Considering the first specimen without chemical etching, fatigue initiation did not anymore occur on porosities or unmolten regions, but on the capillary surface. The second specimen was therefore additionally chemically etched to reduce the capillary surface roughness. Chemical etching improved the capillary surface roughness. The unmolten metal powder particles were removed from the capillary surface and the capillary diameter was enlarged by 150µm. Fatigue initiation did not anymore occur at the capillary surface. The fatigue initiation site was found to be located subsurface close to the tensile stressed corner of the four-point bending specimen. Fatigue performance of the test specimen with chemically etched capillary of the eSHM system was significantly improved to 1130MPa as compared to 820MPa without chemical etching.

HIPping improved fatigue performance of Ti-6Al-4V specimens produced by laser based PBF as compared to the as-built conditions. The additional chemical etching process improves the quality of the capillary surface of the eSHM system, thereby preventing fatigue initiation at the capillary surface. Future work will expand this test campaign to more test specimens and reducing the capillary diameter to further reduce the impact of the capillary on the test specimen.

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Author Contributions: D.D.B. developed the four point bending test set-up and test procedure. M.H. conducted the fatigue tests and fractographic analysis. The conclusions are based on discussions between M.H., D.D.B. and P.G.

Conflicts of Interest: The authors declare no conflict of interest.

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