Very high-cycle fatigue behavior of additively manufactured Ti-6Al-4V using ultrasonic fatigue machine and self-heating testing

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Abstract
Accelerated characterization of high-cycle fatigue properties is necessary in order to enable the optimization of parameters of additive manufacturing processes such as LPBF (Laser Powder Bed Fusion). Therefore, two accelerated characterization methods are applied and compared on Ti-6Al-4V samples produced using the LPBF process. The first method uses an ultrasonic fatigue machine and the second one determines the fatigue limit using self-heating testing. To study the interactions between the material and the accelerated testing methods, fatigue tests are carried out on different grades of Ti-6Al-4V-LPBF differing by their microstructure or their porosity. Three grades have the same microstructure but different porosity levels and three grades have different microstructures with the same porosity. Both properties showed a strong impact on VHCF strength and affected the mechanisms at fatigue crack initiation.

1. Introduction
Ti-6Al-4V alloy printed with LPBF (Laser Powder Bed Fusion) is a promising materials-process combination with potential applications as structural parts. The durability of structures produced with additive manufacturing technics still requires many investigations. Indeed, many LPBF parameters can influence the process-induced porosity or microstructure and thus their high-cycle fatigue behavior. In this context, a rapid determination of these properties is mandatory in order to optimize process parameters with respect to fatigue properties, especially in high and very-high cycle fatigue (VHCF) domains. On possible method uses ultrasonic fatigue machines that enable rapid VHCF testing thanks to their high loading frequency. This frequency is typically 20 kHz, which divides testing time by a factor of about 1000 as compared to conventional testing. Ultrasonically tested specimens are solicitated at their first longitudinal eigenfrequency. Fatigue limit assessment using self-heating testing is another fast characterization approach. In this method, the threshold stress between two self-heating regimes is determined and used as an estimation of the fatigue limit. This study aims to compare these two testing methods. In order to study the effect of microstructure and porosity on fatigue properties and their interaction with the testing method, tests are performed on different material grades. These grades have different porosity levels or microstructures.

2. Results
Fatigue specimens with different Ti-6Al-4V grades were obtained with different processing routes. Three grades have the same microstructure but different porosity levels and three grades have different microstructures with the same porosity. Using different LPBF parameters, parts with two reproducible porosity levels were generated. The first level ($P_1 \approx 0.02$ %) is close to the optimum level in LPBF parts whereas the second one ($P_2 \approx 1$ %) is downgraded. Following printing, three distinct microstructures were generated with different thermal treatments. The one treated at 650°C has ultrafine lamellar with a width of α-lamellae of 0.4 µm. A lamellar microstructure with α-lamellae 1.6 µm wide is obtained after treatment at 920°C. The third one, treated at 1020°C, has equiaxed grains that are 200 µm wide. A third porosity level ($P_0 \approx 0$ %) is produced by a hot isostatic pressing (HIP) post-treatment giving the same microstructure as the one at 920°C. Before testing, porosity levels of some fatigue specimens were analyzed using X-ray micro-tomography. No pores were detected within the HIPed specimens that were scanned.

Results of the ultrasonic fatigue testing are presented in Fig.1. Fatigue resistance is strongly affected by porosity and microstructure. Among grades with the same porosity level, $P_1 - 920°C$ has the highest fatigue resistance. Grain coarsening in $P_1 - 1020°C$ lead to the lowest resistance. The optimal thermal treatment temperature seems to be close to 920°C. Predictably, fatigue resistance decreased with increasing porosity. Porosity going from P_0 to P_2 lead to a 250 MPa drop in fatigue resistance. Moreover, the scatter of results within each grade was related to the different types of pores acting as fatigue crack initiators (Fig.1). Different mechanisms of fatigue crack initiation were observed: pore-induced or microstructure-induced ones. Within each grade, as soon as the grain size was larger than the pores, initiation was microstructure-induced and microstructural facets were visible on fracture surfaces. It should be noted that fatigue crack initiation site was internal in almost all specimens.

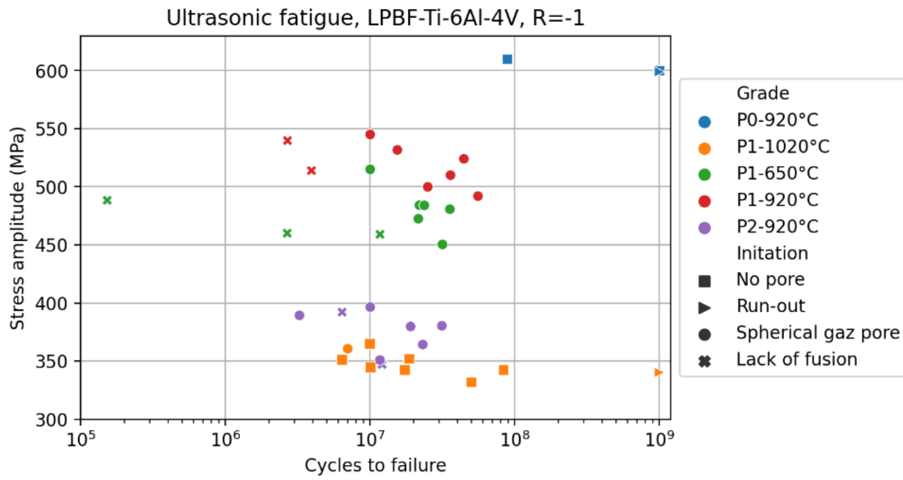

Fig.1 - SN curve from ultrasonic fatigue testing results. Results are presented according to the material grade (porosity, microstructure) and the type of fatigue crack initiation.

Self-heating testing was performed on specimens of the five material grades. Testing consisted of loading steps lasting 50 cycles with increasing stress amplitude. During testing, the temperature of the specimen was measured with a lock-in infrared camera. The lock-in signal was the force signal. This allows extracting the temperature drift, the temperature component synchronous at the mechanical frequency, A_f, and the one at the second harmonic, A_{2f}. For this material, although the second harmonic A_{2f} was increasing with stress amplitude, it did not show a clear shifting from one self-heating regime to another. Moreover, A_{2f} did not show discrimination against specimens of different material grades. However, thermal drift presented at a strong second regime at high-stress amplitudes. Threshold stress between the two regimes was influenced by material grade and can be used to estimate fatigue limit.

3. Conclusions

Parts of TI-6Al-4V were printed with a very low porosity rate close to 0.02 % using the LPBF process. Therefore, it reached high fatigue resistance with a fatigue limit close to 500 MPa after simple thermal treatment. This resistance can be enhanced to 600 MPa using a HIP post-treatment. Ultrasonic fatigue testing was shown to be sensitive to the specific microstructure and process-induced porosity of the LPBF process. The size of grains and pores strongly affect the VHCF behavior of LPBF-TI-6Al-4V.

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