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Théo Dusautoir, Bruno Berthel, Siegfried Fouvry, Paul Matzen, Klaus-Dieter Meck. Influence of post-processing treatments on the fatigue behavior of notched additive manufactured TA6V: Rapid fatigue characterization using staircase procedure and infrared techniques. FATIGUE DESIGN 2021, 9th Edition of the International Conference on Fatigue Design, CETIM, Nov 2021, Senlis, France. hal-04238981

HAL Id: hal-04238981

<https://hal.science/hal-04238981>

Submitted on 12 Oct 2023

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Influence of post-processing treatments on the fatigue behavior of notched additive manufactured TA6V: Rapid fatigue characterization using staircase procedure and infrared techniques

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Abstract

Engineering structures are routinely subjected to cyclic multiaxial stress states, the additive manufacturing (AM) process offers new opportunities for manufacturers to reach designs that can be tailored to the specific solicitations. The aim of this study is to characterize the High Cycle Fatigue (HCF) behavior of 3D printed Titanium alloy (i.e., TA6V) subjected to cyclic multiaxial stresses involving a stress gradient representative of the loading applied to a mechanical component (coupling). Thus, fatigue tests were conducted on TA6V notched specimens obtained with Selective Laser Mating (SLM) process. In addition to the staircase procedure, a thermographic approach using an infrared camera was applied on this particular material to quickly and easily compare different specimen configurations.

The additive manufacturing process has made significant progress since few years and so the possibilities that it offers as well, i.e., lighter parts, fast build, and optimized designs. John Crane, which is a global leader in the design, development and providing of mechanical seals, filtration systems and power transmission couplings has found an interest to explore the potential of AM by developing couplings prototypes. A flexible coupling is a device used to connect two machines at their shaft ends for the purpose of transmitting torque, it is designed to accommodate misalignment and absorb shock loads (cf. Fig. 1).

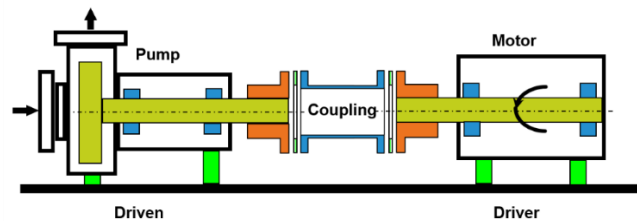


Fig. 1. Power transmission coupling.

In operation, these mechanical parts are subjected to complex multiaxial fatigue loading with stress gradients induced by the geometry and the misalignments. Therefore, it is necessary to properly characterize the behavior of these parts under fatigue loading to ensure a sufficient fatigue life. However, the layer-built strategy used in additive manufactured process creates defects and microstructures that differ from those seen in conventional metals (DeRoy et al. 2018). The fatigue performances of AM parts are altered by the presence of porosities (Le et al. 2020), residual stresses and high surface roughness (Sanaei and Fatemi 2020). As this technology is used for critical engineering solutions, post-processing treatments are generally used to ensure the required mechanical properties. The fatigue behavior is not only related to the previously mentioned defects but to the microstructure as well. Consequently, in this study the influence of mechanical surface finishing and heat-treatments on the fatigue properties of TA6V alloy obtained by SLM (Selective Laser Melting) are investigated. The surface roughnesses and microstructures of different specimen configurations are presented in the next figure. Microblasting using ceramic microbeads supplied by Zirpro is a simple and rapid process that results in a much-improved surface finish compared to the as built specimens (cf. Fig. 2).

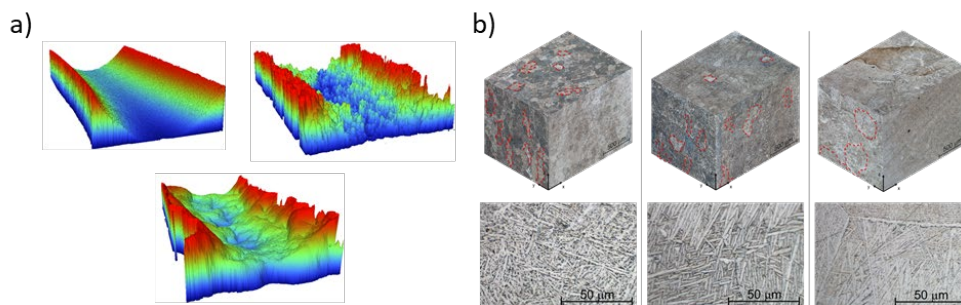


Fig. 2. a) Notch surface texture of reference TA6V, microblast AM TA6V, as built AM TA6V. b) Microstructures at different scales of as built, Sub-transus and super transus heat treated AM TA6V

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Although John Crane has all the facilities to test the couplings in industrial conditions, the production of several AM couplings would be cost prohibitive. It has been shown that the bridging the gap between life prediction of conventional laboratory fatigue tests specimen and real life component is even more difficult for AM parts because of the volume effect (Edy et al. 2020). Therefore, a choice has been made to design an equivalent specimen instead of using conventional fatigue test specimen geometry.

Three matters were identified as critical:

- Fully characterize the cyclic loading: Couplings undergo cyclic, multi-axial stresses due to shaft misalignment, the complex geometry, and to a lesser extent, the AM process itself. As a result, the cyclic loading will be reduced to an equivalent cyclic scalar value calculated using multiaxial fatigue criterion.
- Allow for the effect of high stress gradients: The geometry obtained from topology optimization algorithms can be highly complex and prone to high stress gradients, which are known to influence the fatigue life (Papadopoulos and Panoskaltis 1996).
- Consider the volume effect: It is known that the fatigue performance of a part can be influenced by its size because of the probability to encounter a material defect.

Following this strategy, we came up with a double semicircular notch rectangular bar design.

For this work, an alternative method to the staircase has been used to rapidly compare different material configurations, i.e., infrared thermographic technique. This technique rests on the assumption that the specimen temperature evolution during a fatigue test can be related to microplasticity mechanism and thus the fatigue limit (Luong 1998). From a single thermal signal thermoelasticity and dissipation (microplasticity) can be separately estimated by an overall thermal drift θ_d and two periodic signals at f_L and $2f_L$ where f_L is the loading frequency (Berthel et al. 2014).

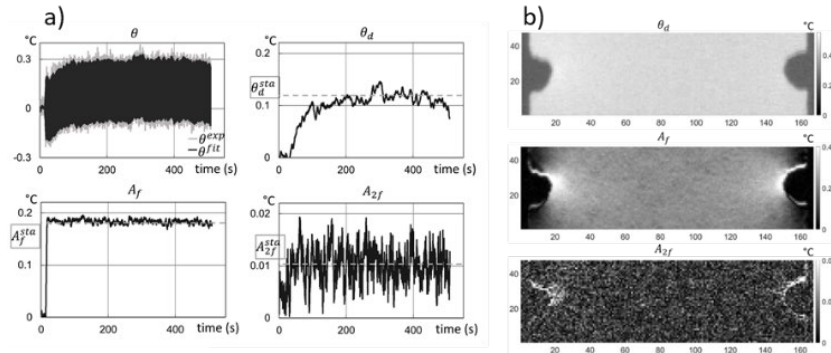


Fig. 3. a) Evolution of: θ^{exp} , θ^{fit} , θ_d , A_f and A_{2f} during one bloc load. $\sigma_{max} = 530MPa$, $R = -1$, $f_L = 30Hz$ and $f_s = 19Hz$. b) θ_d , A_f and A_{2f} 2D maps from a notch to another extracted during a bloc load of 15000 cycles, $\sigma_{max} = 650 MPa$ and $R = -1$ of Shot peened AM TA6V

The fully reversed uniaxial fatigue tests ($R = -1$) are conducted on an MTS servo-hydraulic testing machine at a frequency of 40 Hz. The Wöhler curves and the evolution of the stabilized amplitude A_{2f}^{sta} (result from the infrared thermographic technique) of different tests specimen configurations are displayed on the Fig. 4. Note that the results are normalized according to the reference material fatigue limit. The AM as built material resulted in the lowest fatigue limit and was 50% lower than the reference material. This result is not surprising, it is principally explained by the surface roughness of AM parts that generates localized stresses facilitating crack initiation. The results show that the fatigue limit is increased by 50 % when the specimens have been microblasted. The evolution of A_{2f}^{sta} match the fatigue behaviors because the slopes changes occur at stresses close to the determined fatigue limits. Indeed, it is difficult to estimate properly the fatigue limit from this figure, but this method permits an easy and rapid comparison of different material configurations.

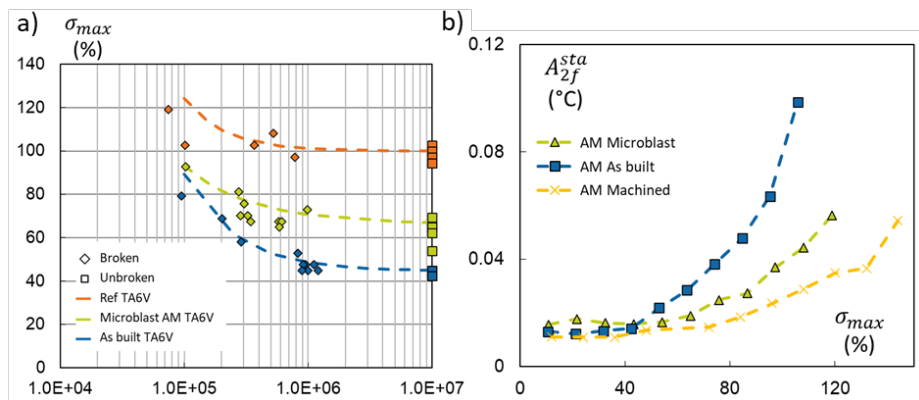


Fig. 4. a) Wöhler curves of TA6V notched specimen for $R=-1$, $f_L = 40 Hz$. b) Evolution of the stabilized second amplitude according to the stress for different surface finish treatment

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