Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 41 (2022) 317–325

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

2nd Mediterranean Conference on Fracture and Structural Integrity

Numerical, Mechanical, and Metallurgical analyses of an innovative lightweight titanium conrod additively manufactured

Silvia Cecchel[a], Seyed Mohammad Javad Razavi[c], Francesco Mega[a], Giovanna Cornacchia[b], Andrea Avanzini[b]*, Davide Battini[b], Filippo Berto[c]

[a]Streparava SpA, Via Zocco 13, 25030 Adro (BS), Italy
[b]Department of Mechanical and Industrial Engineering, University of Brescia, via Branze 38, 25123 Brescia, Italy
[c]Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

Abstract

This study presents findings of an investigation on the reduction of the weight of a critical engine component manufactured by means of additive manufacturing technologies. The component under examination is a Ti6Al4V connecting rod (conrod) having a non-conventional optimized structure produced with SLM. Thanks to the capabilities of the AM technologies, the innovative near net shape design allows: the manufacturing of a lightweighted part, the reduction of some difficult machining operations, and the integration of conformed cooling channels into the part. To take full advantage of these potential benefits, a careful work is necessary to carefully consider all the aspects connected with the product development to ensure the feasibility of replacing the traditional and consolidated manufacturing methods for serial production in the automotive field. In this work we present a summary of the research activities carried out and in progress to assess the innovative conrod design, including selection of heat treatment after experimental characterization of mechanical properties, finite element analyses of the component and fatigue tests on a full-scale prototype, integrated with metallurgical investigations and fracture surface analyses. These activities helped to identify critical locations for fatigue performance, which could pave the way to potential future improvements (i.e. post-processing and re-designing specific component regions based on local methods for fatigue prediction).There is currently very limited literature about the development and testing of actual SLM Ti6Al4V parts and the results of the present work are also a first test bench toward the definition of procedures for the fatigue assessment of real additively manufactured full-scale components.

---

* Corresponding author.
E-mail address: andrea.avanzini@unibs.it

10.1016/j.prostr.2022.05.037

Keywords: Additive Manufacturing;Conrod;Fatigue;Titanium alloy

---

1. Introduction

Transport of people and goods is one the main sources of air pollution and car manufacturers and their suppliers are facing increasingly stringent legislations aiming at the reduction of emissions from vehicles. One of the most effective approach to comply with the targets set by international regulatory bodies is weight reduction, which directly results in reduction of fuel consumption and emissions of the vehicles (see Helms et al. (2007), Cecchel (2021), Cecchel et al. (2021)). Moreover, lightweight structures also bring the additional advantage of improved performances in terms of acceleration, braking and handling.

In this context, Additive Manufacturing (AM) technologies have proved to be extremely useful since they potentially allow the design of innovative components by following the principle of using material only where it is needed. In particular, a peculiar advantage of AM is the possibility to actually manufacture complex shapes, such as those generated by topology optimization algorithms or with generative design. The application of design approaches based on the combination of topology optimization and AM in the context of automotive industry remains challenging and several factors must be evaluated when considering the substitution of a part manufactured with conventional methods with a new one, optimized and fabricated with AM.

The present study presents findings of an investigation on the reduction of the weight of a critical engine component manufactured by means of additive manufacturing technologies. The component under examination is a Ti6Al4V connecting rod (conrod) having a non-conventional optimized structure produced with SLM (Cecchel et al. (2021)). Thanks to the capabilities of the AM technologies, the innovative near net shape design allows: the manufacturing of a lightweighted part, the reduction of some difficult machining operations, and the integration of conformed cooling channels into the part.

To take full advantage of these potential benefits, a careful work is necessary to properly consider all the aspects connected with the product development to ensure the feasibility of replacing the traditional and consolidated manufacturing methods for serial production in the automotive field.

First of all, the mechanical properties of AM materials are highly dependent on the specific printing process and may change as a function of the several parameters that need to be specified. The microstructure of AM materials is also different from that of the equivalent material manufactured with conventional methods, such as casting or forging (Qiu et al. (2012)). Moreover, heat treatments may drastically change these properties and their effects must be carefully investigated. In addition, structural components for automotive applications must often be designed against fatigue. Unfortunately, the current knowledge of fatigue of additive materials is largely incomplete and it can be affected by several factors including surface treatments or processing parameters, as reported for titanium alloys in Benedetti et al (2018), Günther et al. (2017), Chastand et al. (2016), Leuders et al. (2013), Wycisk et al. (2013), Kahlin et al. (2020), Pintado et al. (2020), Morettini et al. (2019), Edwards et al. (2013). In particular, one of the key advantages of AM is the possibility to obtain near-net shapes, avoiding the need of machining operation. In general, fatigue properties in the as-built condition are lower than the counterpart conventional material, as reported for example in Solberg (2019) for titanium alloys. Moreover, while several investigations have been published in literature concerning the influence of surface or internal defects, there is a lack of data on fatigue properties when scaling at component level, which are limited to a few components for aeronautics (see Romano (2017)).

In this respect, it is also quite relevant that shapes resulting from topological optimization often include regions with small curvatures or notches that may cause stress concentrations. While this can affect the life of the component, it is difficult to include fatigue evaluation in the optimization loop and proper fatigue failure criteria should be validated.

In this work we thus present a summary of the research activities carried out and in progress to assess the innovative conrod design, including selection of heat treatment after experimental characterization of mechanical properties, finite element analyses of the component and fatigue tests on a full-scale prototype, integrated with metallurgical investigations and fracture surface analyses. These activities helped to identify critical locations for fatigue performance, which could pave the way to potential future improvements (i.e. post-processing and re-designing specific component regions based on local methods for fatigue prediction). There is currently very limited literature about the development and testing of actual SLM Ti6Al4V parts and the results of the present work are also a first test bench toward the definition of procedures for the fatigue assessment of real additively manufactured full-scale components

2. SLM Conrod

2.1. Topologically optimized design

A connecting rod (conrod) is a very critical engine component, essentially subjected to alternating direct compressive and tensile forces due to the force acting on the piston as gas pressure and inertia of the reciprocating parts. The conrod is usually manufactured by forging mild carbon or alloy steels, depending on engine type. For some niche applications, in which high performances are required, titanium alloys are applied to further reduce the weight (see Froes (2004), Schauerte (2003)).

In a previous research study by Cecchel et al. (2021), an innovative approach based on topological optimization of the component under investigation was presented, in order to explore the possibility of using Selective Laser Melting (SLM) in substitution of the most conventional manufacturing processes for high performance engine. This original patented design (see Fig.1) consists of a SLM multi-branch structure that potentially yield a weight reduction of 45% and 15% in comparison with the "H" section of the forged component considered as reference, made of steel or titanium respectively. Further advantages include avoiding the difficult machining operation to separate the cap from the main body, and the integration of conformed cooling channels into the part.

Fig. 1. Multi branch topologically optimized conrod, Cecchel et al. (2021)

The conrod is made of Ti6Al4V alloy and after the completion of the topology optimization phase, some prototypes and specimens for investigation on material properties were produced, using commercial powder from EOS GmbH and DMLS machine EOSINT M290.

2.2. Mechanical properties and metallurgical analyses

In order to investigate the properties of SLM Ti6Al4V and identify the best heat treatment (HT), a complete characterization of mechanical and metallurgical properties was carried out, considering both As-Built condition and different types of HT. As discussed by Cecchel et al. (2020), two different types of HT were considered, at low and high temperature. In particular, low temperature treatments consisted in a stress relief at 800°C for 4 h or 730°C for 2h. High temperature treatments included instead two steps, super-βtransus or sub-βtransus solubilization followed by tempering. All heat treatments were conducted under high vacuum (10^{-6} mbar) with a "TAV H3 all metal" furnace. The cooling step was performed by using argon (cooling rate 9 $°Cs^{-1}$) after high temperature treatments and in furnace (cooling rate 0.09 $°Cs^{-1}$) for the low temperature treatments. After a thorough investigation on tensile response, presence of residual stress and corrosion resistance, a super-β transus solubilization at 1015°C for 0.5h followed by a tempering at 730°C for 2h was selected. The stress-strain curve of SLM Ti6Al4V after the treatment is reported in Fig. 2, including for comparison purposes the stress-strain curve of the forged counterpart. The experimental mechanical properties measured are yield stress σ_y=900 ± 7 MPa, ultimate tensile strength σ_m=974 ±11 MPa and elongation at fracture A%= 11 ±0.3.

As reported by Cecchel et al. (2020), after the heat treatment the material exhibited an equiassic and isotropic microstructure composed of a mixture of thin α lamellae and β phase, which is expected to be more resistant at fatigue stresses. A representative optical micrograph is reported in Fig. 3.

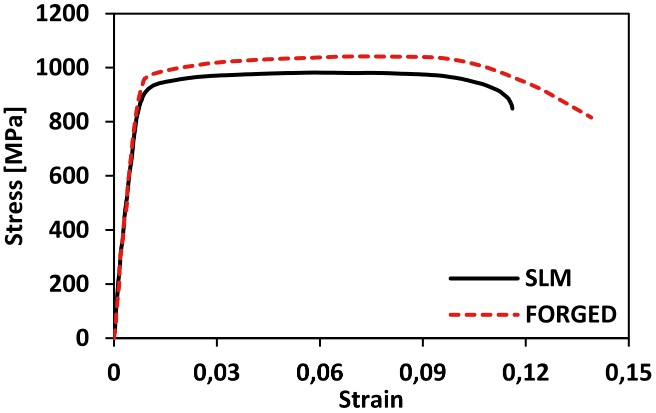

Fig. 2. Stress-strain curves of forged and SLM Ti6Al4V – Adapted from Cecchel et al. (2020)

Metallurgical analyses were first carried out on the samples and then repeated in different section of a conrod prototype that was printed in the same printing job. Overall, the microstructure of the full-scale component after the selected heat treatment was similar to the one observed at the specimen level and characterized by high quality with no relevant defects.

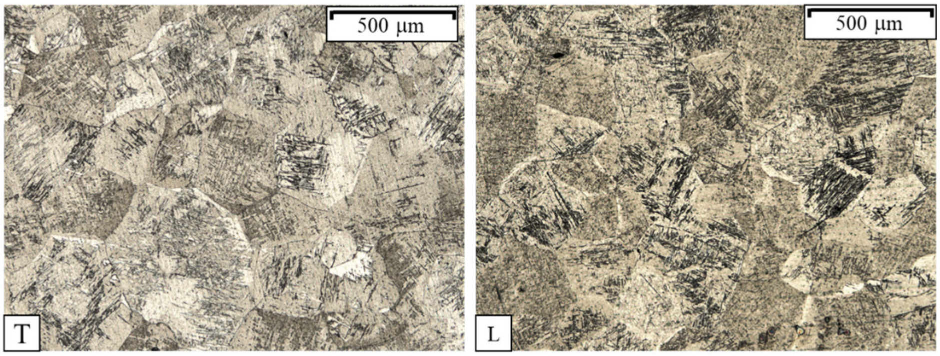

Fig. 3. Optical micrographs with representative microstructure of SLM Ti6Al4V after HT on transverse (T) and longitudinal (L) sections

3. Fatigue testing

3.1. Fatigue test setup and results

Full scale fatigue tests were carried out on the conrods by prescribing axial load cycles under tension and compression. The specimens were loaded using two pins and due to the high compressive load to be applied, a special fixture was used to allow proper connection and alignment of the conrod to the test machine (see Fig.4).

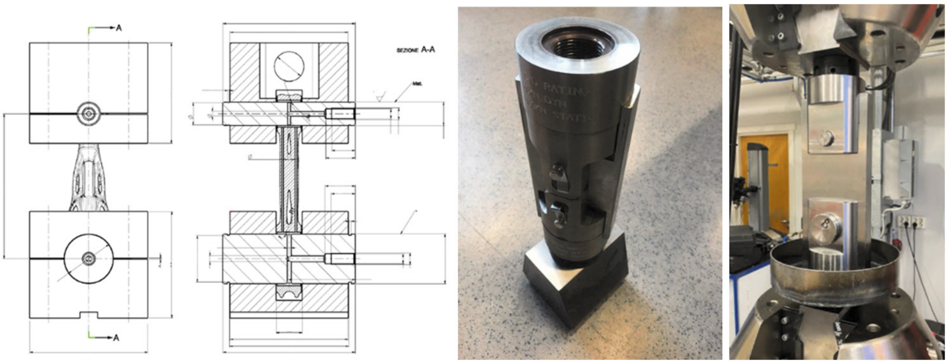

Fig. 4. Load scheme for fatigue test and fixtures for mounting and alignment

The contact surfaces of the loading pins and the bearing holes were continuously lubricated during the course of fatigue loading. The lubrication system included a peristaltic pump with 1 bar oil pressure at the crank end bearing and drip lubrication at the piston pin end, taking advantage of conformed cooling channels integrated into the branches of conrod structure previously mentioned.

The target life was set to 2×10^6 cycles and tests with different values of maximum and minimum load were completed, while keeping fixed the load ratio (R = -2.66) and the loading frequency of 10Hz.

A summary of the fatigue test results is reported in Fig. 5, in which load are normalized with respect to the highest load level (+29 kN / -77 kN), the SLM multibranch conrod exhibited a reduced fatigue strength when compared with the conventional forged solution.

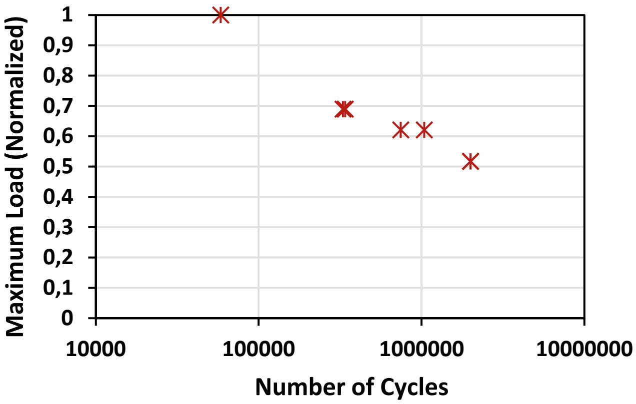

Fig. 5. Fatigue test results

By decreasing the load levels, with the same load ratio, the life of the conrod progressively increased and run-out at 2×10^6 was achieved with a load level corresponding to about half the highest applied load.

3.2. Fatigue failure

A representative failure location and the corresponding fracture surface of the tested conrod specimens under fatigue loading is represented in Fig. 6. The failure regions included outer struts that connect the central region to the big end and the notch at the connection between the big end and the central region. In this area a few surface defects (characteristic size 100-200 µm) were found and according to the optical and scanning electron microscopy results, two initiation points were detected on the fracture surfaces, with parallel fatigue crack growth on both sides of the conrod part through the thickness. In general, no presence of any type of internal defect in the fabricated part was observed, confirming the high printing quality of the bulk material. Detailed inspection of the fracture surface around the lubrication channels also confirmed the lack of fatigue crack initiation in these locations.

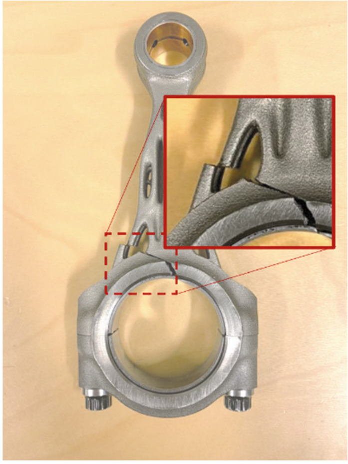

Fig. 6. Representative fatigue failure locations

4. FEM model of the conrod under fatigue test

4.1. FEM model set up

For a better interpretation of the results of fatigue testing, a FEM model of the actual test configuration was implemented. A schematic representation of the loads and constraint applied is provided in Fig. 7. Pins were modelled as rigid surfaces (black), whereas bushings were not included in the analyses. The small-end pin was unconstrained along the connecting rod axis, to allow movement in the loading direction. The big-end pin was completely blocked with all the DOF being constrained.

Two symmetry planes for the testing conditions (dark red and dark green) and a prescribed preload were also considered for the bolted connection (orange surfaces) of the big-end. Pin-conrod interaction was considered frictionless, whereas a coefficient of friction of 0.5 was introduced for the contact between the two halves of the big-end.

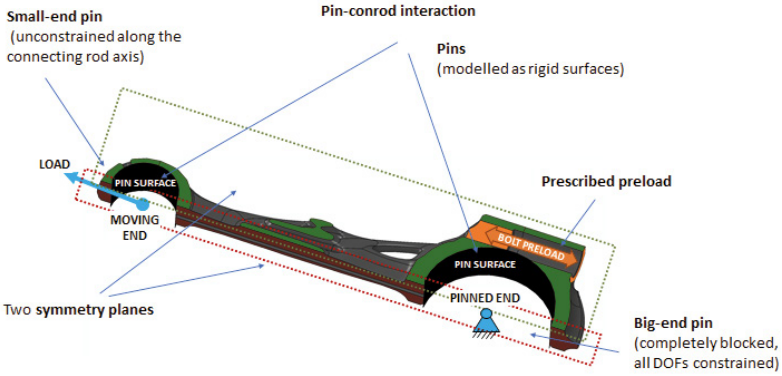

Fig. 7. FEM model with boundary conditions, loads and contact interactions

The mesh consisted of roughly 160000 second order tetrahedra with an average characteristic length lower than 0.8 mm, reaching over 800000 degrees of freedom (DOF) total. An elastic modulus of 123000 MPa and a Poisson coefficient of 0.34 were considered, no plastic behavior was introduced.

4.2. Results of FEM simulation

FEM simulation of the test condition provided useful insights on the stress flow along the branches of structure in different load phases. A first relevant observation is that including contact interaction between the pins and the bearing surfaces is essential, since when shifting from the tensile to the compressive phase the contact regions between the pins and the bearing surfaces of the conrod ends are different.

As a consequence, the stress distribution for the two loading phases of the cycle, tension and compression, are different, as shown in Fig. 8. This is also important from a modelling point of view, since contact interaction obviously involve non-linearity and increased computational time in comparison with alternative approaches, as for example idealized bearing constraints.

The location of the most stressed regions was in very good agreement with the failure locations observed experimentally. In Fig. 9, a detail of the principal stress directions in the area where failure occurred experimentally is also reported.

In general, the stress values observed in this critical region were well below the static strength of the material, but unfortunately the comparison with fatigue strength data for life prediction was not possible yet, due to the lack of data on fatigue strength of SLM titanium alloy under the selected HT.

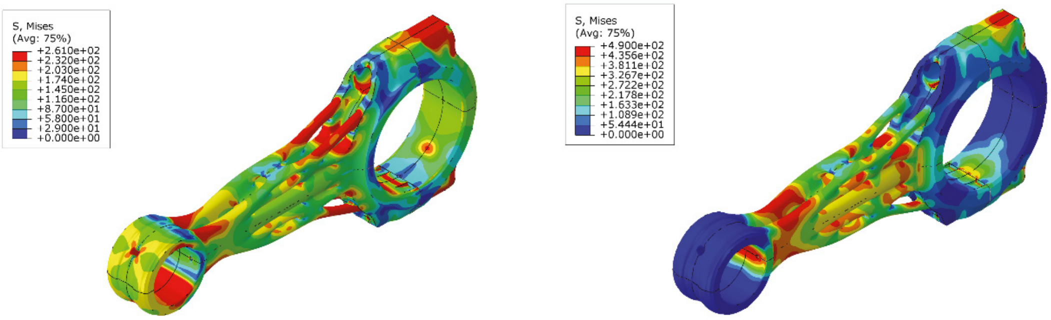

Fig. 8. Von mises stress distributions in (a) tension, (b) compression

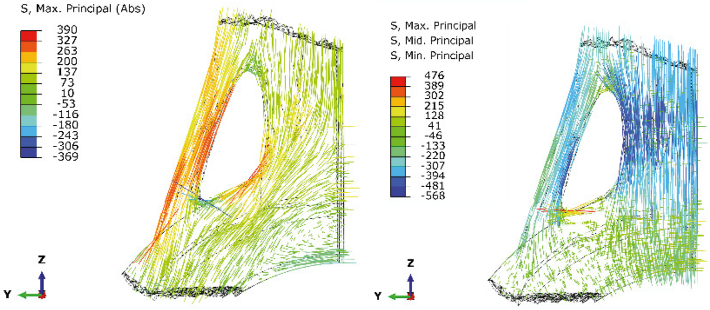

Fig. 9. Directions of principal stresses in the region where failure occurred (a) tension, (b) compression

Considering the combination of FEM and experimental failure analyses, the fatigue resistance of the conrod seems to be controlled by the interaction between stress concentrations, related to the peculiar geometries generated by topological optimization, and surface defects, which are nearly inevitably present when the final shape is obtained without machining operation, although blasting should improve this aspect (see Avanzini et.al, 2019).

5. Conclusions and future work

Fatigue behaviour of topologically optimized Ti6Al4V connecting rods fabricated via selective laser melting was evaluated by performing stress analysis on the designed component and experimental testing of the fabricated parts under applied loads representative of operating service.

The results of fatigue testing indicate that for the current design the fatigue strength of the SLM conrod is lower than the conventional forged solution, nevertheless the proposed approach, based on topological optimization, seems promising. Considering the combination of FEM and experimental failure analyses, the fatigue resistance of the conrod seems to be controlled by the interaction between stress concentrations, related to the peculiar geometries generated by topological optimization, and the presence of a few surface defects, which are nearly inevitably present when the final shape remains in the as-built condition. This suggests that by including in the design phase a fatigue evaluation step and by looking for methods to improve surface characteristics, a significant improvement of conrod durability could be obtained.

In this respect, the activities carried out so far, not only helped to identify critical locations for fatigue performance, but could also pave the way to potential future improvements (i.e. post-processing and re-designing specific component regions based on local methods for fatigue prediction). In order to achieve these goals, further testing campaigns are already planned to evaluate the real fatigue limit of SLM Ti6Al4V after selected heat treatment and calibrate local fatigue failure criteria. The specimen types will include notched configurations, with root radius similar to those present in the actual conrod, angled building orientations to account for the peculiar shape and geometry of the branched structure.

Finally, there is currently very limited literature about the development and testing of actual SLM Ti6Al4V parts and the results of the present work are also a first test bench toward the definition of procedures for the fatigue assessment of real additively manufactured full-scale components.

Acknowledgements

The authors are grateful: for the cooperation during the Design for Additive Manufacturing development to Additive Mind department from EOS GmbH; for the support in the machine tool design and manufacturing to Streparava Spa, particularly to ing. Matteo Magni and ing. Luca Cordioli; for the heat treatments execution to TAV vacuum furnaces SpA, particularly to ing. Alessandro Fiorese and ing. Andrea Gionda.

References

Avanzini, A., Battini, D., Gelfi, M., Girelli, L., Pola, A., Petrogalli, C., Tocci, M., 2019, Investigation on fatigue strength of sand-blasted DMLS-AlSi10Mg alloy,Procedia Structural Integrity, 18, p. 119-128

Benedetti, M., Fontanari, V., Bandini, M., Zanini, F., Carmignato, S. 2018. Low- and high-cycle fatigue resistance of Ti-6Al-4V ELI additively manufactured via selective laser melting: Mean stress and defect sensitivity. Int J Fatigue 107, p. 96–109.

Cecchel, S., 2021. Materials and Technologies for Lightweighting of Structural Parts for Automotive Applications: A Review, SAE Int. J. Mater. Manf. 14(1), p. 81-97

Cecchel, S. Ferrario, D., Panvini, A., Cornacchia, G. 2018. Lightweight of a cross beam for commercial vehicles: development, testing and validation; Materials and Design 149, p. 122–134.

Cecchel, S., Ferrario, D., Mega, F., Cornacchia, G. 2021, Titanium near net shape engine components from Selective Laser Melting: a comparison with the conventional forged parts, Advanced Engineering Materials.

Cecchel, S., Ferrario, D., Cornacchia, G., Gelfi, M. 2020. Development of heat treatments for Selective Laser Melting Ti6Al4V alloy: effect on microstructure, mechanical properties and corrosion resistance, Advanced Engineering Materials.

Chastand, V., Tezenas, A., Cadoret, Y., Quaegebeur, P., Maia, W., Charkaluk, E. 2016. Fatigue characterization of Titanium Ti-6Al-4V samples produced by Additive Manufacturing. Procedia Struct Integr, p.3168–76.

Edwards, P., Ramulu, M., 2014. Fatigue performance evaluation of selective laser melted Ti–6Al–4V, Mater Sci Eng A 598, p.327-337.

Froes, F.H., Friedrich, H., Kiese, J. et al. 2004, Titanium in the family automobile: The cost challenge, JOM, 56, p. 40–44.

Günther, J., Krewerth, D., Lippmann, T., Leuders, S., Tröster, T., Weidner, A., et al. 2017. Fatigue life of additively manufactured Ti–6Al–4V in the very high cycle fatigue regime. Int J Fatigue 94 p.236–45.

Helms, H., Lambrecht, U., 2007. The potential contribution of light-weighting to reduce transport energy consumption, Int. J. Life Cycle Assess. 12, 58–64.

Kahlin, M., Ansell, H., Basu, D., Kerwin, A., Newton, L., Smith, B., Moverare, J.J., Improved fatigue strength of additively manufactured Ti6Al4V by surface post processing, Int J Fatigue 2020;134:105497. https://doi.org/10.1016/j.ijfatigue.2020.105497

Leuders, S., Thöne, M., Riemer, A., Niendorf, T., Tröster, T., Richard, H.A., et al. 2013. On the mechanical behaviour of titanium alloy TiAl6V4 manufactured by selective laser melting: Fatigue resistance and crack growth performance. Int J Fatigue 48, p. 300–7.

Morettini, G., Razavi, S.M.J., Zucca, G. 2019, Effects of build orientation on fatigue behavior of Ti-6Al-4V as-built specimens produced by direct metal laser sintering. Procedia Struct Integr 24, p. 349–59.

Pintado, C.N., Dominguez, J., Perinan, A., Garcia, M.H., Lasagni, F., Bernarding, S., Slawik, S., Mucklich, F., Boby, F., Hackel, L., 2020, Effect of surface treatment on the fatigue strength of additive manufactured Ti6Al4V alloy, Frattura ed Integrità Strutturale 14(53), p. 337-344.

Qiu, J.W., Liu, Y., Liu, Y.B., Liu, B., Wang, B., Ryba, E., Tang, H.P., 2012, Microstructures and mechanical properties of titanium alloy connecting rod made by powder forging process, Materials and Design, 33, p. 213–219.

Romano, S., Brandão, A., Gumpinger, J., Gschweitl, M., Beretta, S. 2017, Qualification of AM parts: Extreme value statistics applied to tomographic measurements. Mater Des, 131, p. 32 –48.

Schauerte, O., 2003, Titanium in Automotive Production, Advanced engineering materials, 6, p. 411-418.

Solberg, K. Berto, F., 2019. What is going on with fatigue of additively manufactured metals? Mat Design Process Comm, 1e84

Wycisk, E., Emmelmann, C., Siddique, S., Walther, F. 2013. High Cycle Fatigue (HCF) Performance of Ti-6Al-4V Alloy Processed by Selective Laser Melting. Adv Mater Res 816–817, p. 134–9.