TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special I, February, 2024

OPTIMIZATION AND 3D PRINTING OF A FLIGHT CONTROL SYSTEM FOR MOTH HYDROFOILING BOAT

Matteo PERINI, Sasan AMIRABDOLLAHIAN, Ciro MALACARNE, Mattia CABRIOLI, Matteo VANAZZI

Abstract: *The International Moth Class is a high-performance foiling dinghy. The Moth needs a system to control the angle of attack of the daggerboard flap and maintain ride height to ensure stability throughout the entire speed range. In this work, we initially employed the Design for Additive Manufacturing (DfAM) methodology as the primary approach to minimize material consumption while preserving stiffness and consolidating different components to reduce compliance in the bowsprit assembly. A weight reduction of 32% was realized along with a 44% reduction in front cross-section area to improve the aerodynamics of the component. Furthermore, the components were fabricated through laser powder bed fusion (L-PBF), using recycled titanium grade 5 powder to improve the sustainability of the design.*

Keywords: *Additive Manufacturing, Moth class, DfAM, L-PBF, Titanium*

1. INTRODUCTION

International Moth Class is a one-person high-performance ultra-lightweight foiling dinghy identified by its exceptional performance and technical innovation. Originally developed in the 1920s, the class has undergone substantial advancements over the years due to the dedication of sailors and designers seeking to optimize the design and maximize speed. Since 2000, this class has incorporated hydrofoils on both daggerboard and rudder, to lift the entire hull above the water surface, lowering the drag and allowing for remarkable speeds by exploiting the power of the wind through the sail. Its innovations have revolutionized high-performance sailing and have attracted both experienced sailors and enthusiasts alike. Compared to traditional foiling boats, the Moth needs a system to control the angle of attack of the daggerboard flap and maintain ride height to ensure stability throughout the entire speed range. It can fly in winds as light as 5 knots and reach speeds of over 36 knots. In this system, lightweight, high stiffness, and corrosion resistance are of utmost importance to ensure an almost frictionless movement. In this regard, researchers and designers continually push the boundaries of technology and hydrodynamic principles in order to improve the International Moth class dinghy[1].

Metal additive manufacturing (MAM) has attracted extensive attention within the scientific and industrial communities in recent years. These innovative methods make it possible to fabricate complex metal components with unprecedented design flexibility by utilizing metal powders and layer-wise additive techniques. The advantages of MAM are numerous[2], [3]. It enables the production of complex geometries and internal structures that were previously impossible to realize through conventional manufacturing (CM) processes. The technique also substantially lowers material waste, improving cost-effectiveness and environmental sustainability. Moreover, rapid prototyping and manufacturing of custom-designed metal components contribute to shorter lead times and greater market responsiveness. Laser Powder Bed Fusion

(LPBF) also known as selective laser melting (SLM), is the most exercised MAM technique [4]. In this method, the component is realized via layer-by-layer selective consolidation of metal powders using a laser beam to melt and fuse the powders. The ability to control the microstructure and mechanical properties of manufactured parts through parameter optimization and scanning strategy makes it an ideal solution for critical applications. In order to achieve the full potential of this innovative manufacturing process, Design for Additive Manufacturing (DFAM) is a crucial factor. This requires designers to adjust their approach to take advantage of its unique capabilities while ensuring that they remain mindful of its inherent limitations. Optimizing build orientations, minimizing overhangs, and optimizing supports are some of these considerations. The latter instance, in particular, has a significant impact not only on the post-processing costs for support removal but also on the mechanical characteristics and residual stresses due to its effect on heat dissipation. Moreover, by combining alloys specifically designed for AM with new design strategies, such as topology optimization, lattice structures, and functional gradients, greater efficiency and mechanical performance can be achieved [5]–[7].

Ti-6Al-4V is a widely used and well-established titanium alloy in L-PBF technology. The outstanding strength-to-weight ratio and its good corrosion resistance, make it suitable for aerospace, biomedical, and automotive applications[8]. There are, however, some challenges associated with the L-PBF process for Ti64 alloy. The high thermal gradients and cooling rates that are characteristics of this process can lead to microstructural heterogeneity and residual stresses in components. Consequently, a carefully designed post-processing heat treatment is essential to improve the mechanical properties of the component and reduce the internal stresses. Depending on the expected properties, different heat treatment strategies can be applied to tune the as-built microstructure (acicular α'martensite) by increasing the β phase and coarsening the α phase[9], [10].

In this work, we initially employed the DfAM methodology as the primary approach. The aim was to minimize material consumption while simultaneously preserving stiffness and consolidating different components to reduce compliance, specifically through the utilization of topology optimization techniques. Subsequently, the components were fabricated through L-PBF, using recycled titanium grade 5 powders to further improve the sustainability of the design.

2. MATERIALS AND METHODS

For this study, recycled gas atomized powder provided by F3nice, with a particle size distribution (PSD) of 20-53 µm and a chemical composition of Al 6.1 wt.%, V 3.9 wt.%, and Ti bal. was utilized. Parts were fabricated using a Concept Laser MLAB machine. This machine is equipped with a fiber laser of 100W and a laser spot diameter of 50 µm. Components with relative densities of 99.4 ± 0.2 % were realized using processing parameters of layer thickness equal to 20 µm, laser power of 95 W, hatching distance of 85 µm, and scanning speed of 900 mm/s. Island scanning strategy with a meander laser path was applied with islands of 5×5 mm and with 90-degree rotation between adjacent islands. Density measurements were performed using the Archimedes method.

Two cuboids of $10 \times 10 \times 10$ mm were fabricated on the same build plate for metallographic investigations and microhardness measurements, using the same parameters for the components. Components were cut from the base plate using wire electrical discharge machining (EDM). Standard metallographic preparations were performed on specimens followed by chemical etching using Kroll’s reagent and microstructure was investigated using a light optical microscope (LOM). Microhardness measurements were carried out on the metallographic cross-sections according to the

ASTM E92 standard. Heat treatment was performed under an Argon atmosphere according to the following scenario: Heating up to 840 °C with a heating rate of 3.5 °C/min (4 h), isothermal holding for 2 h, furnace cooling to 500 °C, followed by air cooling.

Topology optimization and DfAM were carried out using nTopology software[11]. The nTopology suite enables users to better define, represent and lock in various design processes, digitally and in a parametric way. With nTopology one can solve advanced manufacturing and engineering problems, generate unique high-performance parts, and share and reuse its workflows changing only the initial models. The automation of the design process is enhanced by the use of implicit modeling and a field-driven approach. This aims for a robust and fully parametric structure design perfect for lightweighting applications, lattice structures, architected materials, and also mass customization.

3. RESULTS AND DISCUSSIONS

The microstructure of parts in the as-built and heat-treated conditions are presented in Fig.1. It can be observed that in the as-built state, the microstructure mainly consists of martensitic α' due to very rapid solidification and the presence of wide columnar prior grains along the build direction is also evident, while in the heat-treated state, $\alpha' \rightarrow \alpha + \beta$ transition has occurred and a more homogeneous microstructure is obtained. Consequently, microhardness measurements demonstrated a slight hardness drop from 385 ± 9 to 369 ± 7 HV1.

In this work, we initially employed the DfAM methodology as the primary approach. The aim was to minimize material consumption while simultaneously preserving stiffness and consolidating different components to reduce compliance, specifically through the utilization of topology optimization techniques. Topology optimization is the most common type of structural optimization.

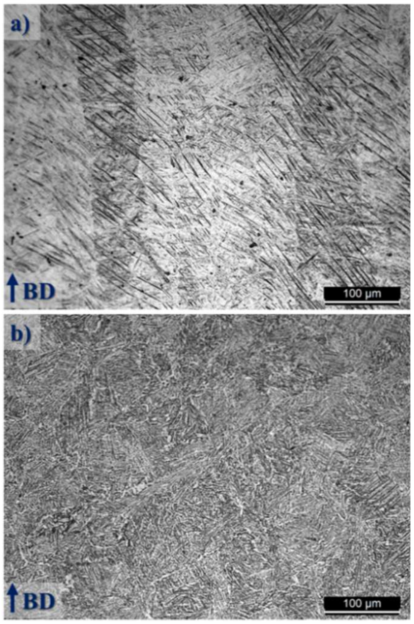


Fig. 1. LOM microstructure of specimens along build direction; a) as-built, b) after heat treatment

It is a mathematical approach that given a design space, tries to optimize material layout. For this application, we used the solid isotropic material with penalization (SIMP) technique that consists of predicting an optimal material distribution within a given design space, for specific boundary conditions, load cases, and manufacturing constraints[12]. The SIMP method works by assigning a density to each finite element. The density of an element can range from 0 (void) to 1 (solid). The objective function is then modified to include a penalty term for elements with low densities. The penalty term is typically proportional to the cube of the density so that elements with very low densities are heavily penalized.

As discussed earlier, compared to traditional foiling boats, the Moth needs a system to control the angle of attack of the daggerboard flap and maintain ride height to ensure stability throughout the entire speed range. Thid system is comprised of a kinematic chain that connects the flap with a movable wand, mounted on the tip of the bowsprit. In this position, the wand can skim the water surface in pristine conditions, avoiding possible turbulences from the hull and foils, and adjust the angle of the flap accordingly. The bowsprit cross-section, both longitudinal and lateral, needs to be minimized to reduce drag and sway. Fig. 2 presents parts of the bowsprit assembly that were selected for topology optimization and shows the difference between the final result of the optimization process and the original design of the mechanism. The approximate dimensions of the parts were 125×70×35mm. The optimization process is then carried out using a numerical optimization algorithm. The algorithm starts with a random distribution of densities and then iteratively updates the densities until a design is found that meets the specified requirements.

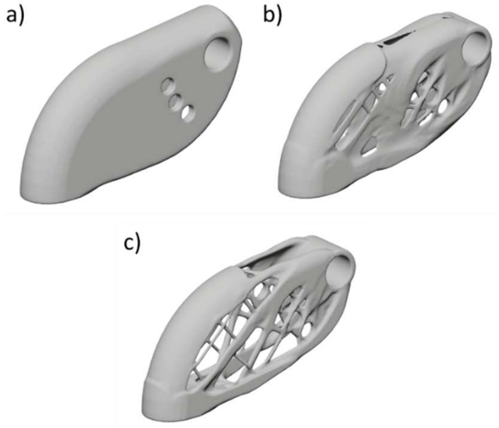
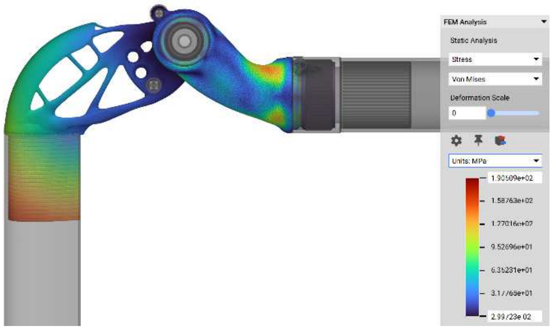


Fig. 2. Schematic of the parts of bowsprit assembly in a) original geometry, b) after 7 iterations, and c) final geometry (21 iterations).

This method can be computationally expensive, especially for large designs. To overcome this bottleneck we leveraged an HPC cluster (64-core CPU, 384 GB of RAM, 48 GB GPU) to run nTop software. Another limitation is that it can be difficult to ensure that the optimized design is manufacturable. For this reason, we introduced the minimum overhang angle (set at 45°) as a constraint. The final design was achieved after four different optimization runs, used to fine-tune the boundary conditions, for a total of 32 hours of computing time.

The optimized design resulting from the SIMP method needs to be finalized in a CAD software and then validated using detailed finite element analysis, for this reason, the Ansys FEA solver was introduced, followed by physical testing on the manufactured component. Compared to the initial design, we were able to achieve a weight reduction of 32% even if the original component was made out of carbon fiber reinforced plastic (CFRP), which has an average density of 1.8 g/cm^3 versus 4.43 g/cm^3 of Ti-6Al-4V.



Static Analysis
Stress
Von Mises
Deformation Scale 0
Units: MPa

Fig. 3. FEM analysis of the stresses on the redesigned component

From an aerodynamic perspective, the front section area has been reduced by 44% and the lateral section by 51%, lowering drag and cross-wind disturbance that previously influenced the ride height precision. Other constraints of the optimization process were to minimize compliance and stress, the resulting FEM analysis displayed a maximum stress of 190 MPa and a maximum displacement of both components below 0.05 mm (Fig3). The rigidity obtained allows the two ceramic bearings (see Fig. 4b) to perform in an almost frictionless condition, thus resulting in a high sensitivity to the rotation of the movable part around the pin axis. The higher the sensitivity, the better the sailor can fine-tune the behavior of the flight control system according to different wind and wave conditions.

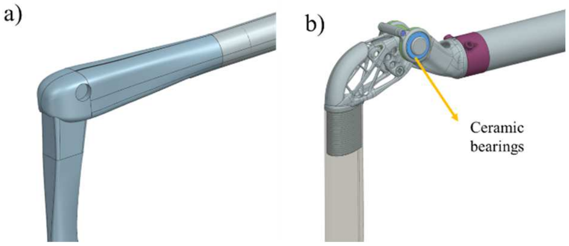


Fig. 4. Schematic of the bowsprit assembly a) original geometry, and b) the final geometry after DfAM

4. SUMMARY

This study effectively demonstrates that the utilization of DfAM in conjunction with L-PBF 3D printing technology for the fabrication of high-performance and lightweight components intended for a competitive watercraft is both viable and advantageous. The devised configuration, meticulously tailored for employment with the Ti6Al4V alloy, facilitates a noteworthy reduction of system mass by 32% in comparison to its initial counterpart. Furthermore, the consolidation of multiple components engenders a heightened mechanical simplicity, thereby facilitating a facile assembly process. This confers a notable advantage in terms of mitigating the propensity for component detachment and loss, particularly in the face of exceedingly rigorous operational environments. Post-process heat treatment was conducted below the beta-transus temperature (980°C) to relieve the residual stresses in the as-built components and modify the microstructure to tailor the mechanical properties and improve the ductility. This customized design improved the setup tunability, allowing the skipper to determine the oversea flight level and the feedback responsiveness of the daggerboard flap pitch angle. Comprehensive testing has been conducted on the system during the last few months, as well as during a competition, and no problems have been reported in terms of functionality and performance. The system has been tested by a world champion sailor, who confirmed a significant improvement in the maneuverability of the boat.

5. ACKNOWLEDGEMENTS

The authors are grateful to **ProM Facility** and **Trentino Sviluppo s.p.a** for letting them use their highly valuable equipment to accomplish their research. The authors wish to thank the world/Olympic champion **Ruggero Tita** for his help during the tests. The authors acknowledge financial aid from the European Community within the Vanguard Initiative through the 3DP Pilot I3 project '3DoP' (Proposal ID. 101083997).

6. REFERENCES

[1] "Rules and Documents – International Moth Class Association." http://www.moth-sailing.org/history/rules-and-documents/ (accessed Aug. 07, 2023).

[2] W. E. Frazier, "Metal Additive Manufacturing: A Review," *J. Mater. Eng. Perform.*, vol. 23, no. 6, pp. 1917–1928, Jun. 2014, doi: 10.1007/s11665-014-0958-z.

[3] S. Cooke, K. Ahmadi, S. Willerth, and R. Herring, "Metal additive manufacturing: Technology, metallurgy and modelling," *J. Manuf. Process.*, vol. 57, pp. 978–1003, Sep. 2020, doi: 10.1016/j.jmapro.2020.07.025.

[4] J.-F. Romainville and F. Bley, "EU Market for 3DP Demonstration Equipment and Services – Final Report," *3DP PAN EU*, Dec. 2021. https://3dppan.eu/ (accessed Mar. 28, 2022).

[5] I. Gibson, D. Rosen, and B. Stucker, "Design for Additive Manufacturing," in *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*, I. Gibson, D. Rosen, and B. Stucker, Eds., New York, NY: Springer, 2015, pp. 399–435. doi: 10.1007/978-1-4939-2113-3_17.

[6] Martin Leary, *Design for Additive Manufacturing - 1st Edition*, 1st ed. Elsevier, 2019.

[7] J. Liu *et al.*, "Current and future trends in topology optimization for additive manufacturing," *Struct. Multidiscip. Optim.*, vol. 57, no. 6, pp. 2457–2483, Jun. 2018, doi: 10.1007/s00158-018-1994-3.

[8] T. S. Tshephe, S. O. Akinwamide, E. Olevsky, and P. A. Olubambi, "Additive manufacturing of titanium-based alloys- A review of methods, properties, challenges, and prospects," *Heliyon*, vol. 8, no. 3, p. e09041, Mar. 2022, doi: 10.1016/j.heliyon.2022.e09041.

[9] F. I. Jamhari *et al.*, “Influence of heat treatment parameters on microstructure and mechanical performance of titanium alloy in LPBF: A brief review,” *J. Mater. Res. Technol.*, vol. 24, pp. 4091–4110, May 2023, doi: 10.1016/j.jmrt.2023.04.090.

[10] M.-T. Tsai *et al.*, “Heat-treatment effects on mechanical properties and microstructure evolution of Ti-6Al-4V alloy fabricated by laser powder bed fusion,” *J. Alloys Compd.*, vol. 816, p. 152615, Mar. 2020, doi: 10.1016/j.jallcom.2019.152615.

[11] “Next-Gen Engineering Design Software: nTop (formerly nTopology),” *nTop*. https://www.ntop.com/ (accessed Aug. 15, 2023).

[12] M. P. Bendsøe, “Optimal shape design as a material distribution problem,” *Struct. Optim.*, vol. 1, no. 4, pp. 193–202, Dec. 1989, doi: 10.1007/BF01650949.

OPTIMIZAREA ȘI IMPRIMAREA 3D A UNUI SISTEM DE CONTROL AL ZBORULUI PENTRU O BARCĂ DE TIP MOTH HYDROFOILING

Rezumat: International Moth class reprezintă o barcă cu foiluri de performanță înaltă. Pentru a asigura stabilitatea pe întregul interval de viteză, Moth necesită un sistem de control al unghiului de atac al aripioarei de sabie și menținerea înălțimii de navigație. În acest studiu, am utilizat în mod inițial metodologia Design for Additive Manufacturing (DfAM) ca abordare principală pentru a minimiza consumul de material în timp ce menținem rigiditatea și consolidăm diferitele componente pentru a reduce deformabilitatea în asamblarea catargului. Am obținut o reducere a greutății de 32%, împreună cu o reducere de 44% a ariei secțiunii transversale din față pentru a îmbunătăți aerodinamica componentei. În plus, componentele au fost fabricate prin tehnologia de fuziune cu pulbere laser (L-PBF), utilizând pulbere reciclată de titan de gradul 5 pentru a îmbunătăți durabilitatea designului.

Matteo PERINI, Ph.D., Additive Manufacturing Engineer, PROM Facility @ Trentino Sviluppo, matteo.perini@trentinosviluppo.it, Tel. +39 338 6454200, Via Fortunato Zeni, 8, 38068 Rovereto (TN), Italy.

Sasan AMIRABDOLLAHIAN, Ph.D., Additive Manufacturing R&D, PROM Facility @ Trentino Sviluppo, sasan.amir@promfacility.eu, Tel. +39 329 0727357, Via Fortunato Zeni, 8, 38068 Rovereto (TN), Italy.

Ciro MALACARNE, Additive Manufacturing Technician, PROM Facility @ Trentino Sviluppo, ciro.malacarne@trentinosviluppo.it, Tel. +39 339 2900156, Via Fortunato Zeni, 8, 38068 Rovereto (TN), Italy.

Mattia CABRIOLI, Ph.D., R&D Manager, f3nice, mattia.cabrioli@f3nice.com, Tel. +39 340 2453585, Via Giulio Uberti, 12, 20129 Milano (MI), Italy.

Matteo VANAZZI, Ph.D., Chief of Technology Officer (CTO), f3nice, matteo.vanazzi@f3nice.com, Tel. +39 340 2453585, Via Giulio Uberti, 12, 20129 Milano (MI), Italy.