26th International Congress of Mechanical Engineering
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-0353
ADDITIVE MANUFACTURING PARTS FOR SONAR AND CAMERA HOUSING OF A SUBSEA CLEANING AND INSPECTION ROBOT

Davi Teodoro Peneluca Vasconcelos
Diego Vieira Barini
Valter Estevão Beal
Juan Carlos Romero Albino
Centro Universitário SENAI CIMATEC, Salvador, BA, Brazil
davit.p.vasconcelos@gmail.com
barinidiego@gmail.com
valter.beal@fieb.org.br
juan.albino@fieb.org.br

Abstract. *Vessels, platforms and other equipment used for oil and gas field exploration and production are prone to work as support to living organisms, especially on tropical and subtropical seas. Nevertheless, fouling from these marine life (seaweeds, barnacles, corals and others) reduce energy efficiency when moving these structures. Also, they can hide corrosion and other defects that can lead to leakages and catastrophic failures. Additionally, when moving from one sea to other sea they can carry sea life and create unbalanced threatens to local sea life. Therefore cleaning of the hulls and structures is necessary. As it is a risk and costly operation, there is an industry movement to robotize the cleaning/removing of the hull fouling. On a robotic solution under development, a camera is needed for supervision of the process and obstacles identification. A Sonar is also added to help the obstacles identification under the water. The first choice was making the supports and housing all made from plates and blanks from milled aluminum alloy. The design team proposed a new solution made entirely from plastic and using Additive Manufacturing, AM. The result considerable reduced the weight to less than 75% in air and also the number of parts, especially bolts. To achieve this optimization, the team used topology optimization and AM design guidelines to propose a design easier to assembly and that can withstand the external pressure of 5 bar and other loads.*

Keywords: *additive manufacturing, topology optimization, robotics*

1. INTRODUCTION

In all types of vessels, hull cleaning is vital to avoid more serious problems such as the accumulation of crustaceans and marine algae in the hull, thus harming the navigation performance and life cycle of the ship (Adland et al., 2018). According to SONG et al. (2020), the variety of methods dedicated to the maintenance of vessel hulls is remarkable, thus demonstrating effective forms of treatment involving automated elements in each process.

Breton et al. (2003) consider process automation the key to a significant evolution in the current competitive scenario, thus minimizing energy costs with manpower and operating time, in addition to reducing the margin of errors during the process. For an "autonomous unit" to be able to identify the impurities present in the hulls of vessels at a depth of up to 50 meters, it is necessary to use a specific set of camera and sonar. Currently, the container that houses such components for capturing information is manufactured by machining in aluminum, having very high mass and greater expenditure of energy, time and material until it is ready to be assembled in its operating position. Thus, it is necessary to use additive manufacturing to optimize the camera-sonar set.

In his study Rosen et al (2014) says that additive manufacturing allows the removal or simplification of processes with multiple steps. With the addition of support technologies such as silicone molding, polishers, drills and others, it is possible to manufacture a wide variety of different parts with different characteristics. Rosen et al (2014) statement is reinforced by the numerous case studies for engineering that focus on adapting complex components through additive manufacturing, as presented in Song et al. (2020). Dilberoglu et al. (2017) present relevant arguments regarding the evolution of processes in the industry and the constant growth of additive manufacturing in this scenario, thus demonstrating a convergent point of view with Javaid et al. (2021), when citing the three most relevant aspects in additive manufacturing: material science, process development and enhancements on design consideration. Also, Ikari et al. (2020) point to the application of additive manufacturing as a solution to reduce waste evaluated by Lean Manufacturing in their processes.

Given this scenario, this study consists of redesigning the camera-sonar assembly (Figure 1), using the Multi Jet Fusion (MJF) additive manufacturing method in order to integrate as many components as possible, reducing the mass in a way significant and eliminate fasteners such as screws, thus facilitating assembly. The multi-jet fusion process for manufacturing polyamide 12 generates excellent visual and structural results in its parts, as stated by Heather J. O'Connor et al. (2018) and Abbott et al. (2021). Finally, the result would bring a model made mostly of polymeric material and manufactured in a single step, thus reducing expenses with materials and operations, as well as simplifying the handling of the equipment in the field.

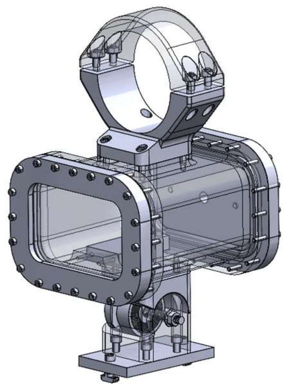

Figure 1. Camera-sonar assembly made in aluminum.

2. METHODOLOGY

A topological optimization study of the camera-sonar assembly (Figure 1) was carried out in order to integrate the sonar support and the base support to the housing, to integrate the back cover while keeping the front cover removable, to replace the cover and support screws of the sonar by locking mechanisms and using a rail system to accommodate the camera inside the system. Locking mechanisms and rails were designed to attend to the new geometries created for these systems.

Cruz (2017) proposed a methodology based on design guidelines for additive manufacturing, which starts from the characterization of the worked materials, geometric optimization steps, structural analysis, prototyping, and finally analysis of the adequacy of quality. The present study differs from the aforementioned methodology, as it even includes the pre-prototyping steps, as well as involving a pre-analysis step of components that can be integrated. Figure 4 illustrates the methodology used to generate results.

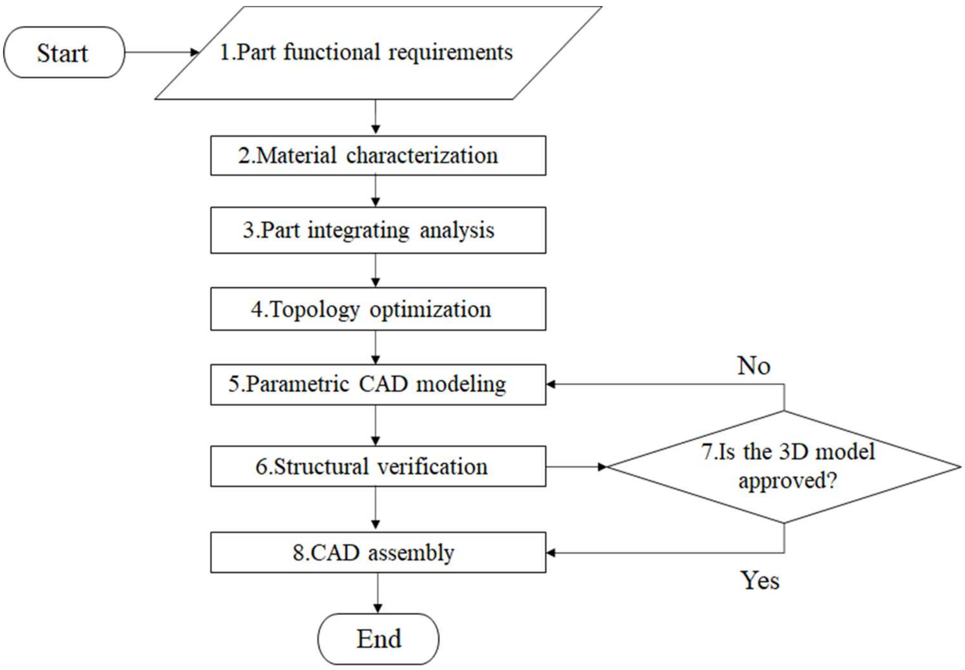

Figure 2. Method for MJF parts design.

As the objective of this work is the 3D printing of the components of the camera-sonar assembly through the Multi Jet Fusion (MJF) process with the Jet Fusion 5210 printer, the material used in the analyzes was polyamide 12 (PA12), which is less sensitive to moisture (Goodridge; Hague; Tuck, 2010), making it suitable for watertight applications.

The procedure used in the characterization of the PA12 material is described below, together with the methodology followed in the component optimization analyses.

2.1 Material characterization

Polyamide 12 (PA12) is a material with non-linear mechanical properties, which implies a stress-strain curve behavior without a well-defined yield point. In this work, the experimental stress-strain curve of PA12 by Morales-Planas et al. (2018) was adopted. According to Erhard (2006), the behavior of this curve up to 4% of the deformation is well described by a fifth-order polynomial. Thus, the interpolating polynomial obtained was

$$S(x) = -0.3408e10 \cdot x^5 + 3.3594e8 \cdot x^4 - 9.8247e6 \cdot x^3 + 0.5972e4 \cdot x^2 + 39.029e2 \cdot x \quad (1)$$

where S is the stress in MPa and x is the strain. The modulus of elasticity was calculated by deriving the interpolating polynomial at the point where the strain is zero, thus obtaining the tangent line at this point. A second tangent line parallel and spaced at 0.5% of the strain in relation to the previous one was drawn, the intersection of which with the stress-strain curve defines the theoretical yield limit of the material. Figure 2 illustrates the procedure described and table 1 indicates the calculated value for the modulus of elasticity and the experimental value according to Morales-Planas et al. (2018). The yield limit obtained was 41.9 MPa which corresponds to a strain of 1.57%.

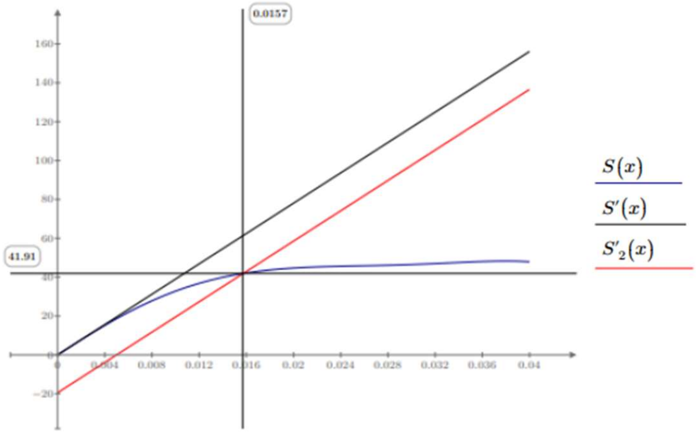

Figure 3. Yield point analysis in the stress-strain curve of PA12.

Table 1. Theoretical vs experimental modulus of elasticity (Morales-Planas, 2018).

	Modulus of elasticity
Theoretical value	3903MPa
Experimental value	4000 MPa

To calculate the allowable stress σ_{allow}, reduction factors were used according to the equipment operating conditions. The reduction factors were applied at the stress corresponding to 80% of the yield strain according to Erhard (2006). Thus, Eq. 2 presents the allowable stress equation with the respective reduction factors.

$$\sigma_{allow} = \frac{K}{S} \cdot \frac{1}{A_T} \cdot \frac{1}{A_{st}} \cdot \frac{1}{A_{dyn}} \cdot \frac{1}{A_W} \quad (2)$$

where K = 37.847 MPa is the stress corresponding to 80% of the yield strain, S = 1 is the safety factor, A_T = 0.998 is a reduction factor for temperature, A_{st} = 1.3 is related to the type of static load, A_{dyn} = 1.3 is related to the type of dynamic load, A_W = 1.007 is regarding the absorption of moisture. According to Eq. (2) an allowable stress of 22.3 MPa was adopted for the design and validation of the topological optimizations presented in this work.

2.2 Loadings and analysis procedure

In the design of the camera-sonar set immersed in water, an external pressure of 6 bar was considered, together with the drag force corresponding to a current of 5 m/s.

In the topological optimization analyses, first, a base CAD geometry was generated for the components, then a linear static finite element analysis was generated, then a topological optimization analysis was carried out seeking to maximize stiffness and reduce the volume of the components, finally, the geometry obtained from the optimization analysis was treated and validated through a new linear static analysis.

The CAD geometry used as the basis for topological optimization analysis is shown in Figure 3, it is composed of housing, sonar support, and base support, for each of these components a topological optimization study was carried out. For housing validation, in addition to static linear analysis, a buckling analysis was performed due to the effect of external pressure.

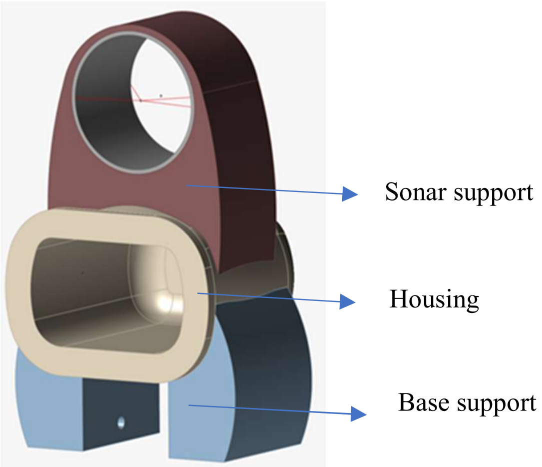

Figure 4. Geometry used as the basis for the optimization study.

3. RESULTS

The first of the optimized components, the housing, is the watertight structure of the equipment. It supports a pressure of 6 bar and holds a camera in its internal space. Figure 4 illustrates how this component was optimized in two different software. The geometry on the left represents the starting geometry for the simulation, with 20mm thick walls. The middle geometry represents the result of the structure optimization through SolidWorks Simulation, finally, the right geometry represents the optimized geometry through the Altair Inspire software. The final geometry resembles a spherical profile to better withstand external pressures. From the results obtained, the geometry presented by SolidWorks was followed to perform parametric modeling.

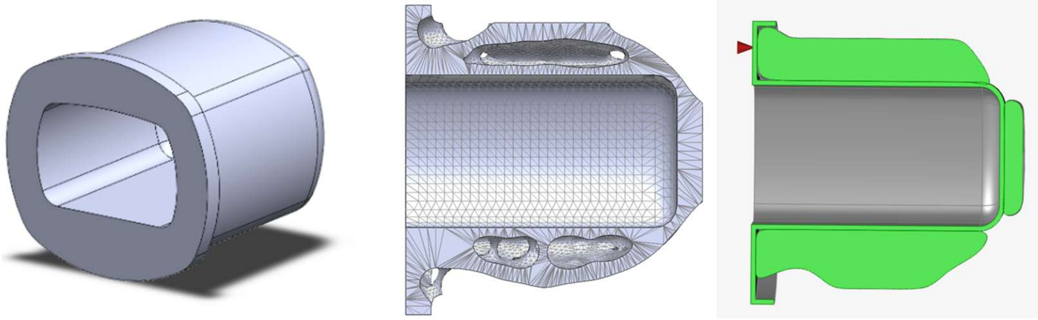

Figure 5. Housing optimization.

Then, the optimized geometry was the sonar fixation system, the sonar support. Due to the complexity of the loading associated with this component, the optimization was performed in two steps. The first step of the analysis considers only the closing force of the upper clamps, which fix the sonar, as shown in Figure 5. For this result, only the region within the area marked in the figure is important for the structure, as it aims to understand the suitable geometry for closing.

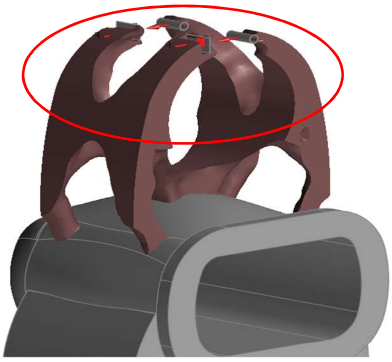

Figure 6. Clamp closing optimization.

The second part of the analysis aims to understand, based on the drag force, how the geometry of the connection interface between the sonar support and the housing should be. The drag force was calculated according to the projected lateral area, admitted as a critical area. Table 4 indicates the parameters used to calculate drag, as well as the results for each region, with region one as a function of the sonar area, and region two as a function of housing. The drag coefficients (*Cd*) and the calculation of the drag force (*Fd*) were performed according to Çengel (2015). Thus, the geometry of the upper region of the sonar support (Figure 6) was modeled with the top connected, seeking a response from the geometry to the lower region. Figure 6 illustrates the results obtained from topological optimizations for this second part of the analysis. Therefore, the final geometry of the sonar support was given as a composition of the results obtained through the optimizations shown in Figures 5 and 6.

Table 2. Calculation of drag force.

CALCULATION OF DRAG						CENTER OF PRESSURE	
REGION	**Fd (N)**	**ρ (kg/m³)**	**V (m/s)**	**Cd**	**A (m²)**	**Z (mm)**	**Y (mm)**
1	276.72	997	5	0.7	0.03	29.69	138
2	373.19			1.05	0.0285	0	0

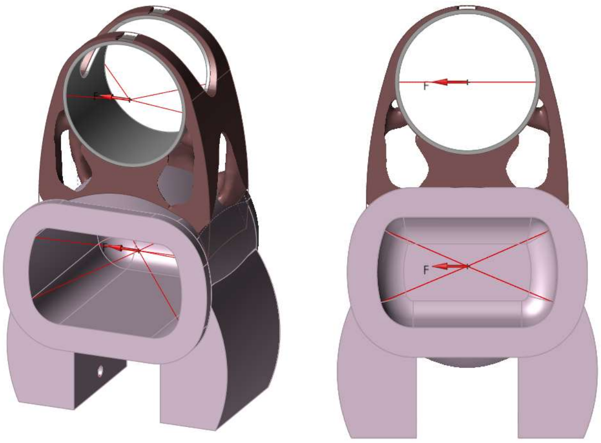

Figure 7. Bottom optimization of sonar support.

Finally, the base support has been optimized. This has two bodies to allow the angular adjustment functionality of the assembly. The solution was designed with the objective of reducing the number of fasteners of the original model made of aluminum, which made it difficult to assemble the set. Figure 7 shows the topological optimizations of the base support for the drag forces as shown in table 2.

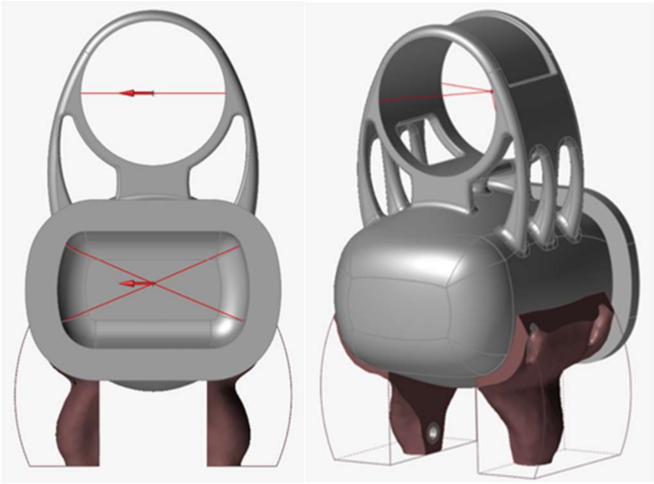

Figure 8. Base support optimization.

Based on the geometries obtained as a response, it was possible to carry out the modeling and assembly of the equipment components as shown in figure 8. Among the components present in the structure, it is also worth mentioning some components with important functionalities that were designed, such as the locking mechanisms of the cover and sonar, as well as the camera's internal accommodation rail.

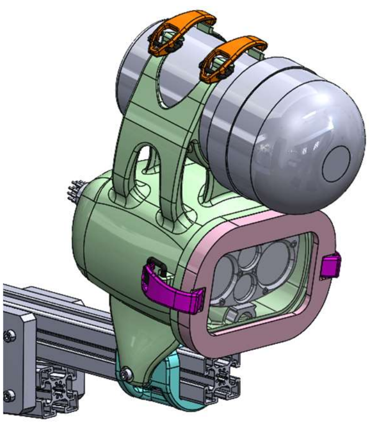

Figure 9. Assembly of the housing.

The comparison between the two assemblies of the equipment, for machined aluminum and for additive manufacturing can be seen in Figure 9. Table 5 shows the mass reduction that was obtained with the project, as well as the total reduction in the number of fasteners with the new concept.

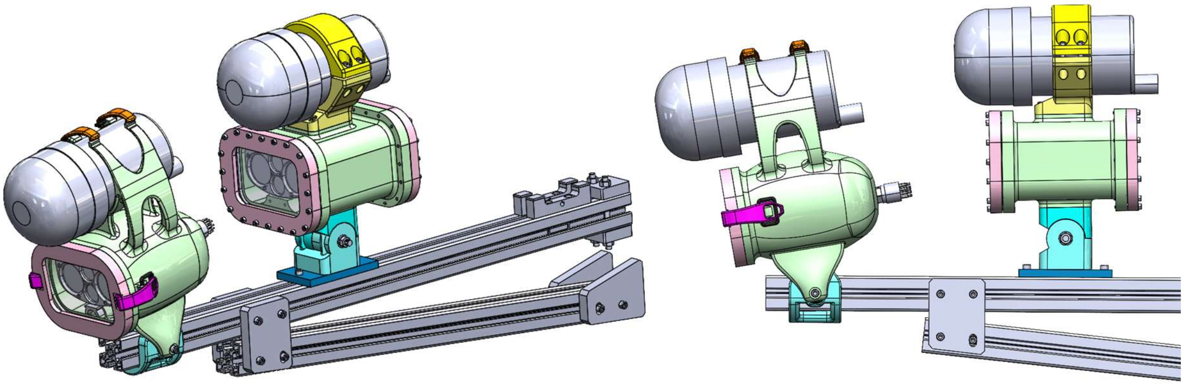

Figure 10. Comparison between aluminum and polyamide 12 CAD model.

Table 5. Comparison of results between the aluminum model and the additive manufacturing model.

Model	Mass (Kg)	Screws
Machined Aluminum Housing	6.15	62
Housing by Additive Manufacturing	1.82	4
Reduction	70%	94%

4. CONCLUSION

When comparing the results arising from the redesign in additive manufacturing with the previous model in aluminum, it is possible to notice a reduction of 70% in the total mass of the set and a reduction of 94% in the number of screws. Thus, with the adaptation of the set for additive manufacturing, it was possible to carry out the manufacturing plan in a single step. The set of benefits demonstrated clearly shows the feasibility of applying additive manufacturing to the initial project.

5. ACKNOWLEDGEMENTS

The authors would like to thank the support of the company HP Brasil Indústria e Comércio de Equipamentos Eletrônicos Ltda, SENAI CIMATEC and SHELL do Brasil. The authors also acknowledge Altair Brasil and 4i engenharia, for providing educational licenses to Altair Inspire and Solidworks Simulation, respectively. This project was funded by HP Brasil using resources based on Law #8.248 of 1982 (Informatics Law).

6. REFERENCES

ABBOTT, C.; SPERRY, M.; CRANE, N. **Relationships between porosity and mechanical properties of polyamide 12 parts produced using the laser sintering and multi-jet fusion powder bed fusion processes**. *Journal of Manufacturing Processes,* Elsevier, 2021. https://doi.org/10.1016/j.jmapro.2021.08.012.

ADLAND, Roar; CARIOU, Pierre; JIA, Haiying; WOLFF, Francois-Charles. **The energy efficiency effects of periodic ship hull cleaning**. *Journal of Cleaner Production*, Elsevier, 2018. https://doi.org/10.1016/j.jclepro.2017.12.247.

BRETON, Richard; BOSSÉ, Éloi. **The Cognitive Costs and Benefits of Automation.** *Defense Technical Information Center*. 2003. Available in: https://apps.dtic.mil/sti/citations/ADA422303. Last access: 19 jun. 2021.

ÇENGEL, Yunus A.; CIMBALA, John M.. **Mecânica dos fluidos: fundamentos e aplicações.** 3. ed. Porto Alegre: Amgh Editora Ltda., 2015.

CRUZ, Marcio Fernando *et al*. **A design for additive manufacturing method of direct metal parts for aerospace applications**. 2017. ABCM: 24th COBEM - 2017.

DILBEROGLU, Ugur; GHAREHPAPAGH, Bahar; YAMAN, Ulas; DOLEN, Melik**. The role of additive manufacturing in the era of Industry 4.0.** *Procedia Manufacturing*, Elsevier, 2017. https://doi.org/10.1016/j.promfg.2017.07.148.

ERHARD, Gunter. **Designing with Plastics**. Munich. Hanser Gardner Publications, Inc., 2006.

GODRIDGE, R.D.; HAGUE, R.J.M.; TUCK, C.J.**. Effect of long-term ageing on the tensile properties of a polyamide 12 laser sintering material.** *Polymer Testing.* 2010. https://doi.org/10.1016/j.polymertesting.2010.02.009.

IKARI, M., RIBEIRO, E., DE FARIAS, E., CANDIDO, F., DE SIQUEIRA, L., & AMARANTE, M. **Aplicação do lean manufacturing em conjunto com a manufatura aditiva na redução de desperdícios em processos.** *Revista Pesquisa E Ação*, 6(1), 81-104. C. U. Braz Cubas. 2020. ISSN 2317-3793

JAVAID, Mohd; HALEEM, Abid; SINGH, Ravi Pratap; SUMAN, Rajiv; RAB, Shanay. **Role of Additive Manufacturing applications towards environmental sustainability**, *Advanced Industrial and Engineering Polymer Research*, Elsevier 2021. https://doi.org/10.1016/j.aiepr.2021.07.005.

O'CONNOR, Heather J; DICKSON, Andrew N; DOWLING, Denis P; **Evaluation of the mechanical performance of polymer parts fabricated using a production scale multi jet fusion printing process,** *Additive Manufacturing,* Elsevier, 2018. https://doi.org/10.1016/j.addma.2018.05.035.

MORALES-PLANAS, S; MINGUELLA-CANELA, J; LLUMA-FUENTES, J.; TRAVIESO-RODRIGUEZ, J.A.; GARCIA-GRANADA, A.A. **Multi Jet Fusion PA12 Manufacturing Parameters for Watertightness, Strength and Tolerances.** *Materials*, MDPI. 2018. https://doi.org/10.3390/ma11081472.

ROSEN, D., GIBSON, I., STUCKER, B. **Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing**. United States: Springer New York. 2014.

SONG, C., CUI, W. **Review of Underwater Ship Hull Cleaning Technologies**. *Journal of Marine Science and Application.* Springer, 2020. https://doi.org/10.1007/s11804-020-00157-z

SONG, Longlong; GAO, Tong; TANG, Lei; DU, Xinxin; ZHU, Jihong; LIN, Ye; SHI, Guanghui, LIU, Hui; ZHOU Guannan; ZHANG, Weihong, **An all-movable rudder designed by thermo-elastic topology optimization and manufactured by additive manufacturing**, *Computers & Structures*, Elsevier, 2021. https://doi.org/10.1016/j.compstruc.2020.106405.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.