

3D Printed Elastomers for the Ocean: Bridging the Gap Between Innovation and Maritime Standards

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ABSTRACT

Modern maritime engineering faces critical logistical challenges regarding the supply chain of elastomeric components, such as seals, gaskets, and flexible conduits. Traditional manufacturing methods impose severe economic and time barriers, including long lead times and a total dependence on centralized shore infrastructure, which are incompatible with urgent emergency repairs at sea. While polymer Additive Manufacturing (AM) emerges as a disruptive decentralized solution, its widespread implementation is bottlenecked by a critical regulatory gap. Current maritime frameworks, such as IACS Recommendation 186, explicitly restrict their scope to metallic alloys, whereas standards like DNV-ST-B203 lack quantitative protocols for hyperelastic and sealing performance validation. Furthermore, long-term service standards like ISO 23936-2 assume absolute material isotropy, a premise broken by the layer-by-layer nature of AM. To bridge this gap, this paper introduces a Unified Qualification Framework (UQF) for marine elastomeric replacements. The UQF integrates structural and process requirements from classification societies with severe fluid aging and Rapid Gas Decompression (RGD) testing, establishing a mandatory validation strategy oriented along the most unfavorable building axis (Z-axis) to account for interlaminar weakness and capillar porosity. Additionally, an operational segregation model is proposed. This framework eliminates the inefficient case-by-case approval bottleneck, providing a standardized technical foundation for classification societies to regulate on-demand marine elastomeric manufacturing.

1. Introduction.

Modern maritime engineering faces a critical logistical challenge: flexible components such as gaskets, seals, flexible con-

duits, vibration dampers, and cable protectors represent predictable wear items whose failure during navigation can demand prolonged replacement lead times through traditional supply chains based on injection molding or compression forming. A vessel requiring an unforeseen onboard emergency repair, in the event that the spare part is unavailable onboard or at port, can face weeks of logistical delays, generating significant additional operational costs due to downtime and the loss of operational windows [14].

Conventional elastomers exhibit mechanical and chemical properties suitable for naval applications, but their manufacturing via conventional techniques imposes economic and temporal barriers such as, for instance, the requirement for geometry-specific molds, minimum production batch sizes, prolonged lead times, and dependence on centralized manufacturers [14]. This

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logistical framework is incompatible with urgent repair scenarios or decentralized production facilities.

Elastomeric additive manufacturing (AM) emerges as a technological alternative to address this logistical gap. 3D printing technologies are capable of processing flexible polymers, even onboard, across various Shore A hardness ranges comparable to conventional marine elastomers, enabling the on-demand production of the replacement component without the need for specific tooling. In this manner, lead times can be reduced from weeks to days or hours (depending on geometrical complexity and parameters selected in the slicing software), so enabling the decentralization of manufacturing capabilities to port facilities, logistical support vessels, or the installation of these technologies directly onboard merchant ships [5] [14].

To ensure the practical viability of the proposed qualification framework, technological selection must not be limited to the intrinsic mechanical properties of the elastomer; it must respond to an operational segregation based on the manufacturing environment. The model presented in this contribution introduces a differentiation between onboard fabrication capabilities (Corrective Maintenance) and shipyard capabilities (Preventive Maintenance and Technical Dry-docks).

The primary contribution of this work is to provide the first systematic evaluation of 3D-printed elastomers from the perspective of naval engineering and maritime regulation, establishing a technical and regulatory foundation that can serve as a baseline for the development of specific standards by classification societies and international bodies.

Section 2 presents the methodology followed in this research. For its part, Section 3 presents the results and conducts a discussion thereof regarding technologies and materials (3.1), analysis of the regulatory gaps (3.2), the proposed evaluation framework (3.3), and the guide for material and technology selection (3.4). Finally, Section 4 presents the conclusions of the work.

2. Methodology.

To achieve the proposed objective, the development of the research is sequentially articulated through the procedural phases shown in figure 1.

Figure 1: Methodology fluxogram.



Source: Authors.

In *phase 1*, a comparative characterization of the two main technology families of elastomeric additive manufacturing is performed, conducting a comparative evaluation of the two main families in terms of mechanical properties, structural characteristics (degree of anisotropy), chemical resistance in marine environments, and operational validation precedents in naval contexts [5]; in *phase 2* an exhaustive mapping of the existing regulatory gap in IACS Recommendation 186, DNV-ST-B203, and Lloyd's Register Polymer AM Guidance Notes is conducted, specifically identifying which aspects of elastomer qualification for naval applications are not covered by existing frameworks [5], [6], [18]; in *phase 3*, a hybrid qualification framework is proposed that merges current additive manufacturing protocols with specific fitness-for-service testing (such as ASTM D4482 for cyclic fatigue [2], chemical resistance, effect of liquids [3], and tensile fatigue [8]), incorporating technical extensions for maritime conditions, incorporating technical extensions for subsea conditions (tests under cyclic hydrostatic pressure and seawater ageing with thermal cycling) in alignment with specifications contemplated by classification societies [5]; in *phase 4*, an AM technology selection matrix is constructed based on operational conditions and the constraints of the naval environment.

3. Results and discussion.

This section presents and analyzes the conducted research in a structured manner to address the feasibility of elastomeric additive manufacturing from a naval perspective. First, Section 3.1 evaluates the available printing technologies, comparing their technical capabilities and limitations for onboard environment applications. Subsequently, Section 3.2 maps the current regulatory gap, identifying the limitations of existing certification frameworks against the requirements of flexible materials. Based on this diagnosis, Section 3.3 presents the proposed hybrid qualification framework to bridge the regulatory gap. Finally, Section 3.4 develops a methodological decision-making tool.

3.1. Materials and technologies for onboard repairs.

This section summarizes the different additive manufacturing technologies that may be viable for onboard use vessels; the first involves *solid filament-based thermoplastic polyurethanes and elastomers (TPU / MEX)*: it depends on the melting and extrusion of flexible filaments through a heated nozzle [7]. The most widespread reference polymer is thermoplastic polyurethane (TPU), as can be seen in Figure 2. This variant presents the highest technological readiness level on the market, low equipment acquisition costs, and a safe operation that does not require complex chemical extraction environments onboard. TPU processed by FFF stands out for its excellent intrinsic resistance to mechanical abrasion, high tear strength in the printing plane (XY), and notable chemical compatibility with oils, greases, and light hydrocarbons for naval use. However, the process generates an intrinsically anisotropic microstructure due to the layer-by-layer deposition pattern; the mechanical and

cohesive properties measured along the stacking direction (Z-axis) are significantly lower than those of the XY plane, conditioned by incomplete thermal diffusion between adjacent filaments and the presence of internal voids.

Figure 2: 3D printed pump diaphragm.



Source: Authors.

The next technology is *liquid silicone rubber extrusion systems based on a tubular consumable (LSR / MEX)*; a disruptive evolution within the MEX family is the processing of two-component Liquid Silicone Rubber (LSR) through a hybrid fluid-filament technology. The operational principle of this technology relies on a flexible tubular consumable that internally encapsulates the two reactive liquid components [15]. The extruder's mechanical traction system draws the tube in a manner analogous to a conventional thermoplastic filament. Inside the print head, the external polymeric sheath is mechanically peeled and removed, while the reactive fluids are simultaneously and volumetrically dosed into a static mixing nozzle. The components are homogenized inside the nozzle and initiate their crosslinking kinetics immediately prior to the deposition of the bead. This technology offers critical advantages for the marine environment: it exhibits complete hydrolytic inertia, excellent thermal stability (-50°C to $+200^{\circ}\text{C}$), and inter-layer coalescence is optimized because the material is deposited in a pre-crosslinked fluid phase, which enhances molecular diffusion compared to the thermal fusion welding of filaments, drastically reducing inter-bead porosity and improving the watertightness of the final component. Its main limitation is that the low initial viscosity of the silicone prior to completing the cure restricts geometric fidelity in severe overhangs or complex structures without the use of specific support materials.

Finally, there is *vat photopolymerization-based stereolithography (SLA / VPP)*; this technology employs a focused laser beam to selectively photocure layers of liquid resin composed of elastic acrylates or epoxies [7]. The major advantage of

SLA technology for naval applications is its microstructural nature: the three-dimensional photochemical crosslinking generates parts with quasi-isotropic behavior and a relative density close to 100%, lacking the interconnected capillary porosity that defines extrusion technologies. This guarantees hermeticity under pressure and surface finishes of high geometric fidelity. Its primary onboard limitations center on the operational complexity of post-processing (requiring washing stations with isopropyl alcohol IPA and controlled UV post-curing chambers), the risk of liquid resin spills due to vessel motion, and a more limited long-term chemical stability, showing susceptibility to UV aging and accelerated hydrolytic degradation compared to industrial TPU or silicones [19].

3.2. Analysis of the Regulatory Gap in Maritime Frameworks.

The adoption of additive manufacturing in shipbuilding has been guided by the development of qualification, approval, and certification frameworks drafted by classification societies and backed by international standards. However, these frameworks exhibit scope limitations that generate specific regulatory gaps for elastomeric materials.

On one hand, DNV-ST-B203 (2025) positions itself as one of the most advanced regulatory frameworks by incorporating specific guidelines for the additive manufacturing of polymers, particularly in Section 7.7 [5]. This section regulates the four key processes described in the ISO/ASTM 52900 standard [7]: material extrusion (MEX), powder bed fusion (PBF), vat photopolymerization (VPP), and material jetting (MJT), representing a qualitative leap for certification in the sector. However, it does not develop specific protocols for elastomers.

On the other hand, IACS Recommendation 186 “Additively Manufactured Metallic Parts for Marine and Offshore Applications” (2025) constitutes one of the first international standards for additive manufacturing in naval applications, developed by the International Association of Classification Societies (IACS). It establishes requirements for process qualification, inspection, mechanical testing, and acceptance criteria for components produced via AM [6]. However, it is exclusively limited to powder bed fusion (PBF), directed energy deposition (DED), and binder jetting (BJT) of metallic alloys; generating a regulatory gap in 3D-printed elastomeric components.

Finally, Lloyd's Register guidelines “Guidance Notes for Polymer Additive Manufacturing” (2025) establish a general framework for process qualification, traceability requirements, mechanical characterization testing, and risk assessment methodology for the approval of AM components [18]. However, the content focuses on polymers for general structural applications, without developing specific procedures for elastomers.

Table 1 summarizes the coverage of current regulations against the requirements of elastomeric additive manufacturing:

The analysis of the previous frameworks reveals that the true regulatory gap does not lie in the lack of rules regarding the use of a 3D printer, but rather in the absolute disconnection between the certification of the manufacturing process and the chemical/mechanical validation of the material in service. While classification societies (DNV, IACS, LR) advance in auditing the printing environment [5], [18], the most demanding

Table 1: Regulatory coverage of current maritime standards for additive manufacturing of elastomers.

Regulation / Guidance	Scope	Covered Processes	Covers Elastomers?	Critical Limitation Identified
DNV-ST-B203 (2025) [5]	AM Polymers	MEX, PBF, VPP, MJT	Not specific	Absence of specific qualification protocols and lack of quantitative thresholds.
IACS Rec 186 (2025) [6]	Metallic Alloys	PBF, DED, BJT	No	Restricted exclusively to metals; total regulatory gap in polymers/elastomers.
Lloyd's Register (2025) [18]	AM Polymers	General	Not specific	Focused on rigid structural polymers; lacking criteria for elastomers.

Source: Authors.

fitness-for-service standards in the offshore sector, such as ISO 23936-2, require elastomers to demonstrate resistance to aging by deleterious fluids and Rapid Gas Decompression (RGD) [9].

The fundamental conflict is that ISO 23936-2 assumes the tested material is completely isotropic and free of internal microvoids (typical of traditional injection molding manufacturing methods) [9]. Given that additive manufacturing intrinsically introduces a marked interlayer anisotropy and microporosities, there is currently no regulatory appendix or standardized methodology determining how to adapt ISO 23936-2 tests to the physical nature of a 3D-printed elastomer [9]. This gap forces the industry to operate under "case-by-case" approvals, a technical and economic bottleneck that hinders commercial on-demand production of gaskets and seals directly in shipyards.

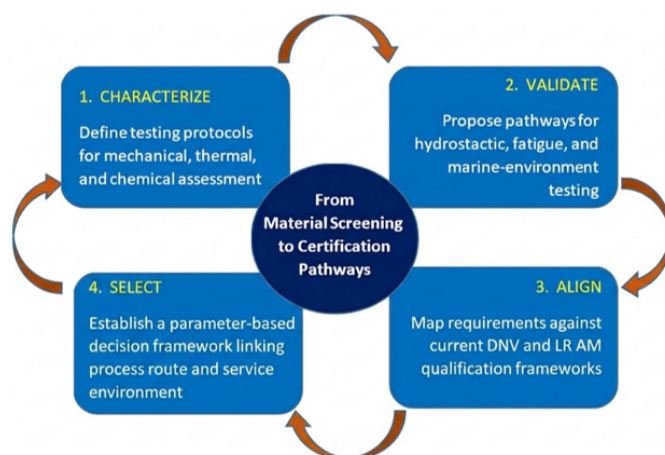
This issue manifests itself primarily in three critical areas: The first is the *material scope*, where existing standards cover metals [6] and rigid structural polymers [5], [18], but do not address the specific behavior of flexible elastomers under marine service conditions; the second area is *the testing dimension*, as AM regulations omit vital tests for fluid seals, such as cyclic fatigue [2], interlaminar tear resistance [11], and long-term compression set analysis [10]; and finally, the *acceptance criteria dimension*, where although regulations mandate the declaration of directional anisotropy dependence [5], none establish quantitative limit values, tolerable interlayer porosity thresholds, or specific compression set ranges for elastomers [9], [10], preventing the definition of when a printed component possesses sufficient quality to guarantee long-term hermeticity.

For this reason, advances in additive manufacturing and new materials necessitate the development of a methodology to select the most appropriate soft elastomeric materials for specific marine applications. There is also a need for comparative analyses that integrate characteristics regarding the degree of anisotropy, chemical resistance, mechanical property validations, and their relationship with the regulation of elastomeric 3D printing in marine applications. Finally, it is necessary to adapt current regulations to new materials and additive manufacturing techniques.

3.3. Proposed Evaluation Framework.

The comprehensive evaluation and selection framework for soft elastomeric materials in marine applications proposed in this work is structured around four key pillars: the first pillar is to *define the characterization of the mechanical, thermal, and chemical properties* of FFF, SLA, and emerging silicone technologies [5], [7]; the second is to *propose validation pathways for operational feasibility* through industrial case studies; the third is to *align the qualification of soft elastomers with established regulatory frameworks* [5], [6], [18]; and finally, to *lay the foundation for a decision-making framework* that enables engineers to select optimal materials based on specific environmental requirements such as depth, temperature, and pressure. The process is shown in figure 3.

Figure 3: Integrated Framework for Characterization, Validation, and Selection of Marine Elastomers..



Source: Authors.

To systematically evaluate the physical performance of the component under this framework, the integration of standardized tensile and elongation testing [1] is proposed, along with cyclic fatigue protocols [2] adapted to simulated hydrostatic conditions to evaluate pressure-induced degradation.

The framework takes as an initial empirical validation baseline the operational success of rigid SLA-printed components that have been successfully deployed in Remotely Operated Vehicles (ROVs) at depths of up to 600 meters. Such hydrostatic performance is fully supported by the quasi-isotropic microstructure resulting from the dense three-dimensional photochemical crosslinking characteristic of VPP technology.

Nevertheless, given that elastic photopolymers possess a significantly lower elastic modulus than their rigid precursors, it is established as mandatory that this quasi-isotropy and the absence of elastic permeability be experimentally validated through specific hydrostatic tests, limiting the direct extrapolation of results.

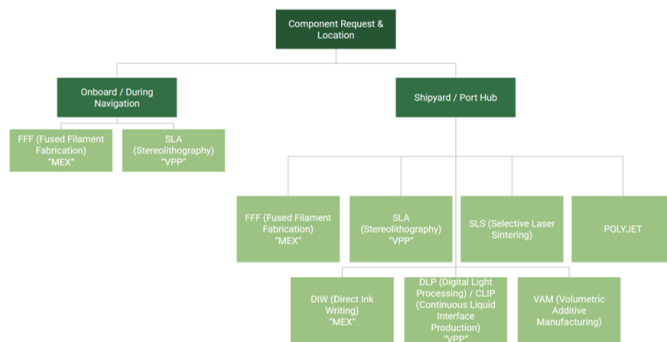
It is here where liquid silicone rubber extrusion systems based on guided filament (LSR / MEX) simultaneously resolve onboard operational limitations and the microstructural deficiencies of thermoplastic FFF. Although these emerging sili-

cone extrusion technologies offer significant advantages, their implementation in critical naval environments remains contingent upon future experimental validation (Compression Set, chemical aging tests [9]) and comprehensive standardization protocols that guarantee their reliability under service conditions.

3.4. Technological Selection Matrix based on Operational Environment and Criticality.

The research conducted in the previous sections enabled the development of an operational selection tool, which is summarized in the matrix shown in figure 4.

Figure 4: Technological Selection Matrix based on Operational Environment and Criticality.



Source: Authors.

During navigation, the system will be conditioned by dynamic instability, vibrations, spatial restrictions, and the impossibility of handling complex chemical post-processings. In this scenario, the only two technologies compatible with elastomers are: *FFF* technology, which is based on the processing of thermoplastic elastomers such as Thermoplastic Polyurethane (TPU), and *SLA*, which is centered on elastic photocurable resins.

The land-based environment eliminates movement and space restrictions, allowing the exploitation of Industrial Additive Manufacturing (AM) systems with high elastic density that suppress the marked anisotropy along the build axis (Z) typical of desktop technologies.

It should be noted that land-based industrial capabilities by no means exclude the use of FFF and SLA platforms in the shipyard. On the contrary, desktop systems (FFF/SLA) harmoniously coexist as the most agile and economical tools for the rapid creation of tooling or geometric fit-testing prior to mass production. The land-based industry thus solidifies itself as an accumulative ecosystem that encapsulates the entirety of the elastomeric technological catalog in additive manufacturing.

4. Conclusions.

This work has systematically evaluated the deployment of elastomeric additive manufacturing (AM) in the naval supply chain, concluding the following key points: regarding the *regulatory gap*, a critical normative void has been demonstrated in current standards. IACS Rec. 186 completely excludes polymers, while DNV-ST-B203 and Lloyd's Register lack protocols

for soft elastomers; on the other hand, the conflict regarding the degree of isotropy arises because fitness-for-service regulations such as ISO 23936-2 assume material isotropy. The FFF process generates capillary porosity that compromises sealing, whereas SLA technology presents a dense quasi-isotropy, suitable for withstanding hydrostatic pressures but subject to slight interlaminar mechanical variations. *The unified qualification framework* is introduced, which, as proposed, resolves part of the existing gap through the use of existing tests; and finally, a *selection guide for AM technologies based on the operational environment* is proposed. The next steps to follow for the correct adaptation of these technologies are to apply empirical laboratory validations, conduct hydrostatic testing, and perform finite element analysis to predict the service life of the spare part prior to its onboard installation.

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