# A comprehensive metal additive manufacturing platform to transform the marine industry

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**Abstract.** Direct Metal Deposition (DMD) is one of the underwater marine additive manufacturing (MAM) technologies known for its capability to build up on semi-finished products. This allows for the creation of complex structures and repair the damaged or worn-out areas. Employing this underwater technology needs a lot of consideration regarding the harsh environment of the ocean. This research endeavours to identify nickel-aluminium bronze's structural characteristics printed underwater. Simulation studies can help to analyse grain and phase evolution, defects, and melt pool behaviour, enabling the optimization of printing parameters for high-quality marine alloy components. To achieve that a control systems and machine learning algorithms need to developed to enhance precision in the 3D printing process on a moving platform, addressing the challenges of six distinct vessel movements at sea. This integration aims to improve accuracy, contributing to optimal performance in dynamic maritime environments.

## 1 Introduction

The operations and maintenance assume a dominant role in the overall expenditure lifecycle of a marine vessel, accounting for approximately 72% of the shipping industry budget [1]. Surface cracking and damage, such as seawater corrosion, abrasion, and surface fatigue cracks, pose substantial risks to marine equipment. These surface issues often precede unforeseen equipment failures, with documented cases demonstrating their direct impact on operational reliability and maintenance costs [2]. Replacing damaged or failed components aboard a vessel is not only an expensive endeavour but also imposes space constraints, making it a challenging task. In the face of these challenges, the marine industry is constantly in search of innovative technologies that can improve efficiency, reduce costs, and overcome inherent limitations.

Metal additive manufacturing (AM) has the potential to bring about a transformative impact on maintenance and repair processes. This approach offers a wide array of benefits, including geometric freedom, the ability to repair high-value components, build-up on semi-finished products, corrosion-resistant and wear-resistant coatings, multi-material capabilities, repair and refurbishment capabilities, efficient thermal management, and surface

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modification. While the current use of AM primarily focuses on controlled land-based environments, its application in off-shore and underwater maintenance and repair can revolutionize the marine industry.

There are certain existing challenges with shipbuilding additive manufacturing. Ship motions, environmental factors, and material properties impact AM processes and component quality. Vessels and floating platforms operating in challenging sea conditions are subjected to significant loads from factors such as wind, waves, currents, and ship vibrations, all of which influence equipment performance and maintenance requirements. Additionally, the unique underwater environment presents its own set of challenges, including water pressure, temperature fluctuations, high humidity levels, and exposure to corrosive elements, which must be carefully considered during the design and implementation of manufacturing and repair systems. Although the literature on underwater AM is limited, several recent studies have initiated exploration in this domain and have made some progress by developing a technique for stable underwater AM, which is currently undergoing laboratory testing [3,4,5].

Extensive research has been performed on 3D printing concrete materials for underwater applications, particularly in infrastructure development and coral reef restoration. Additionally, the development of 3D printing technology has primarily cantered around in situ concrete printing. Additive manufacturing (AM) technology enables the direct construction of concrete structures underwater, providing a more practical and effective method of building [6,7,8].

When in comes to the metal, only a limited number of metals have been studied for use in underwater 3D printing. The most advanced research has been conducted on titanium alloys, e.g., Ti-6Al-4V, to repair marine equipment in underwater environments, employing laser metal deposition (LMD). Researchers utilized a specially designed drainage nozzle to create a localized dry chamber for the process [9]. Results indicated the potential of this technology for fabricating and repairing customized components or parts with complex geometries underwater. The same material and LMD technology were also utilized by Fu et al. [10] to produce thin-walled Ti-6Al-4V alloy parts for assessing the feasibility of repairing underwater structures. In this case, water backflow was prevented through appropriate nozzle design and the use of shielding gas flow, ensuring a stable local dry cavity for printing.

The shipbuilding industry has greatly benefited from the utilization of nickel-aluminium bronze (NAB) alloys since the 1970s, particularly in the construction of high-value ship propellers. These alloys possess an array of exceptional mechanical properties, including high strength, fatigue resistance, toughness, and remarkable resistance to corrosion, erosion, biofouling, and cavitation in seawater environments. Furthermore, NAB alloys offer cost-effective repair options and ease of maintenance when they require attention. Their exceptional resistance to corrosion, corrosion fatigue, and erosion, coupled with their excellent cavitation resistance, make them indispensable for applications involving seawater [9]. There have been some studies conducted on printing NAB with different MAM technology, which has been still limited [11-14]. Integrating a direct metal deposition (DMD) machine underwater technology has the potential to revolutionize maintenance and repair processes. This approach offers numerous benefits such as geometric freedom, repair of high-value components, build-up on semi-finished products, corrosion-resistant and wear-resistant coatings, multi-material capabilities, repair and refurbishment capabilities, thermal management, and surface modification. Additionally, employing a DMD technology to print nickel-aluminium bronze (NAB) alloys overcomes limitations associated with traditional manufacturing methods, providing exceptional corrosion resistance and superior wear properties suitable for marine environments.

## 2 Material and Methods

A comprehensive investigation of strategic marine alloys including NAB material fabricated through the AM technology. Initial microstructure characterizations are also carried out to confirm desired mechanical properties, porosity levels, and hardness values, with micro-CT techniques employed to identify and mitigate pore types for the development of low-porosity materials. The microstructure of the 3D printed NAB material is characterized through different advanced electron microscopy techniques including electron backscatter diffraction (EBSD) and scanning electron microscopy (SEM).

A control system is essential in ensuring precise manufacturing, especially when accounting for the six distinct vessel movements experienced at sea, including heave, sway, surge, roll, pitch, and yaw. By integrating advanced control strategies and machine learning, the aim is to enhance the accuracy of the printed components, thus contributing to their optimal performance and reliability in demanding maritime environments.

As a calibration step to compare with underwater production, the machine is used to deposit NAB in a dry environment. The goal is to meticulously investigate manufacturing parameters, including power, speed, and scanning strategies, to achieve superior part quality with minimal defects. Simulation techniques is used to replicate the unique properties of the underwater environment, ensuring that the final NAB components are optimized for exceptional performance and resilience in submerged conditions.

Finally, comprehensive corrosion tests, including electrochemical measurements and exposure to simulated underwater conditions will be performed as a future work on the samples produce under water to ensure their high quality. Additionally, the long-term durability of underwater printed NAB components will be assessed by subjecting them to extended corrosion tests and monitoring corrosion rates and material degradation over time.

Further to the microstructural characterization and defect analysis, a robust solidification framework consisting of a finite element thermal model along with a cellular automata (CA) platform is developed. This framework can help to predict the cooling rates and analyse grain and phase evolution, assess defects, and scrutinize melt pool behaviour. In addition, this platform can enable the identification of key printing parameters necessary to produce high-quality NAB components, ensuring enhanced performance and reliability.

## 3 Results and Discussion

A DMD machine incorporates a bio-inspired robot designed specifically for underwater repairs is developed in this project. This snake-shaped robot operates in subsea environments, with the capability to swim at high pressures waters can help deposit materials such as NAB underwater. It utilizes scanning capabilities to detect and assess areas requiring repair. With specially designed nozzles, it creates a dry environment for coating or building up the damaged area, facilitating efficient and effective repairs. By combining DMD technology, the bio-inspired robot, and the use of NAB alloys, the machine offers a comprehensive solution to address maintenance and repair challenges in the marine industry, providing enhanced performance, longevity, and efficiency.

While this method offers opportunities for manufacturing and repairing parts underwater, our tests have encountered several challenges. The most significant one relates to porosity and decreased density. Due to varying cooling rates during the process and the influence of water temperature, controlling process parameters consistently throughout the test becomes cumbersome. We maintained a constant laser power and scan speed across all layers, which leads to different types of porosities in different layers. The porosity level poses additional challenges as it affects the microstructure and mechanical properties of the parts produced underwater, making control of these properties challenging. In addition, these defects can have significant detrimental effect on corrosion properties and biofouling characteristics of the final alloy specially in case of marine alloys such as nickel alumina bronzes. To mimic the six movements that occur in real ocean situation, the platform is designed with three-axis movement and three-axis rotation. Figure 1a illustrates the position of the platform and coordinate axes, while the rotation of each point on the platform is shown in Figure 1b. Additionally, the angle of rotation of the platform is depicted in Figure 1c.

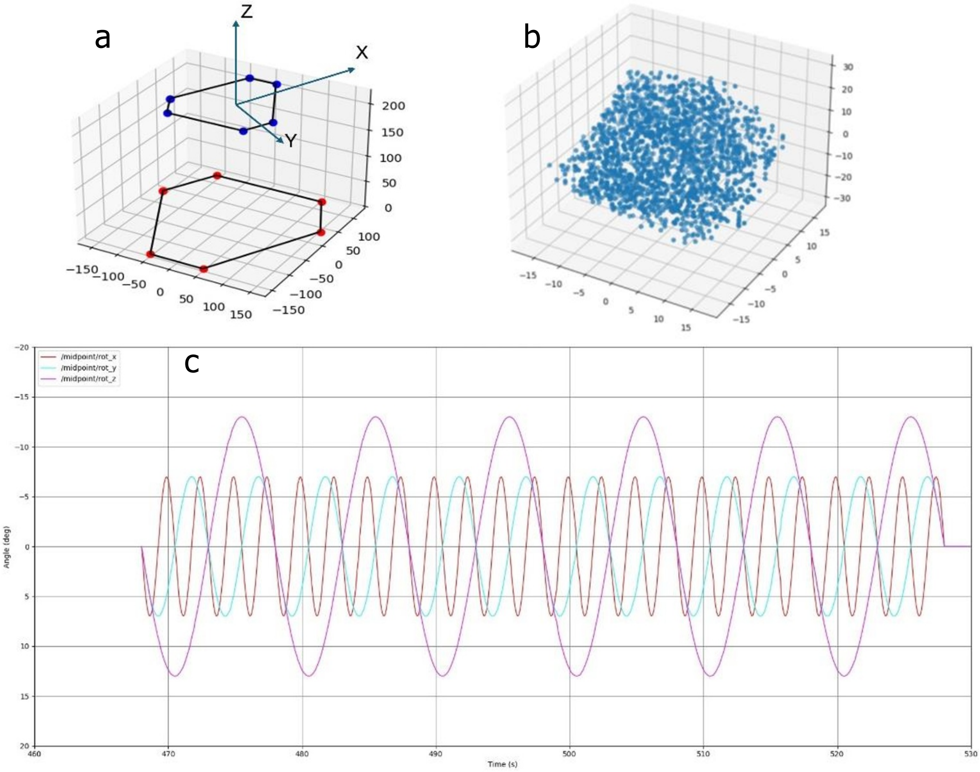

**Fig. 1.** a) Coordinate Axis, b) 3D- Scatter Plot of Rotation X/Y/Z, c) Platform Rotation Diagram

The CA modelling platform offered numerous benefits in predicting the microstructure of metals during AM processes. Firstly, it provides a versatile framework for simulating complex microstructural evolution, allowing for the prediction of grain growth, phase transformation, and defect formation. CA models are computationally efficient, enabling rapid simulation of large-scale systems. They also offer flexibility in incorporating various physical phenomena and material properties, making them adaptable to different metallic alloys and process conditions.

By implementing rules that govern grain growth based on local thermal gradients and solidification kinetics, CA can effectively simulate the elongated, columnar grain structures observed in AM parts. This capability enabled us to understand the way process parameters such as laser power, scan speed, and powder characteristics influence grain morphology, aiding in the optimization of AM process parameters to achieve desired material properties.

CA models can also have some weaknesses, including simplifications in representing the actual physics of the process and the need for accurate input parameters, which may not always be readily available. Furthermore, the scale at which CA frameworks operate can be a limitation, particularly in capturing mesoscale phenomena or interactions at the grain boundaries. Figure 2a shows the cooling rate of the melt pool after the heat source has passed.

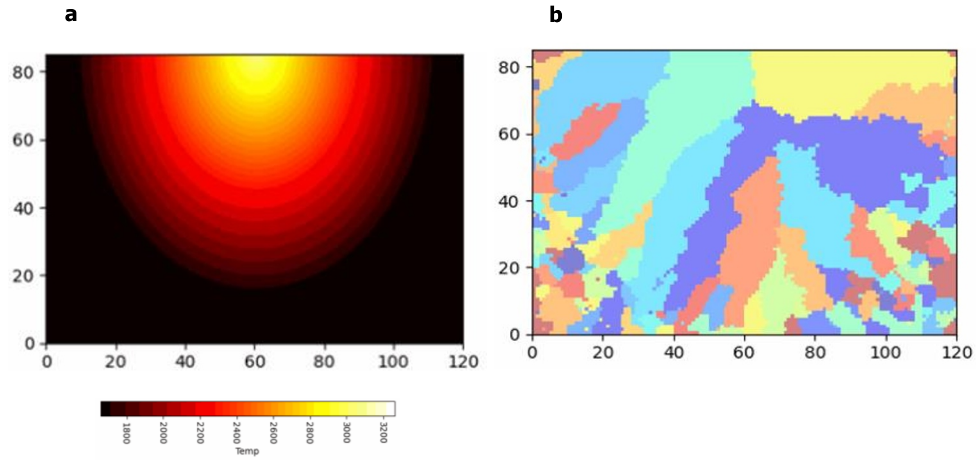

**Fig.2.** a) Melt Pool Temperature Profile, b) Base Equiaxed Grain and Formation the Columnar Grain

## 4 Conclusion and Future Work

Metal AM offers significant advantages in underwater applications. By leveraging its near-net shape capabilities, metal AM facilitates the construction or repair of final parts directly underwater, reducing the necessity for extensive post-processing procedures typically associated with welding. This research aims to advance metal AM technology tailored for marine applications, addressing the distinct challenges of maritime operations. This initiative is poised to revolutionize marine maintenance and provide the cornerstone for launching two pioneering companies—one specializing in underwater AM scopes.

In future research, we aim to utilize alternative methods that are more efficient for simulating this process. The phase field simulation method offers several advantages over cellular automata (CA) for simulating grain boundary formation, solidification, and thermal history during AM processes. Phase field simulations inherently capture the dynamics of evolving interfaces between different phases, allowing for realistic representation of grain boundaries and their evolution over time. Unlike cellular automata, which often rely on simplistic grain growth rules, phase field models can simulate complex grain morphologies, including equiaxed and columnar grains, without the need for predefined parameters. Additionally, phase field simulations naturally account for the effects of thermodynamics and kinetics on solidification, providing more accurate predictions of microstructural features. This includes capturing phenomena such as solute segregation, dendritic growth, and grain boundary migration, which are crucial for understanding material properties in metal AM components. Furthermore, phase field models inherently incorporate thermal history effects, enabling the simulation of temperature gradients and cooling rates experienced during the AM process. This comprehensive representation of solidification and thermal behaviour makes phase field simulations a powerful tool for optimizing process parameters and predicting microstructural evolution in AM parts.

## References

1. Y. Giroux, *The Life Cycle Cost of the Canadian Surface Combatants*, (2022)
2. G. Sun, Z. Wang, Y. Lu, M. Chen, K. Yang, Z. Ni, *Underwater Laser Welding/Cladding for High-performance Repair of Marine Metal Materials:*

*A Review, Chinese Journal of Mechanical Engineering* (English Edition). **35** (2022). https://doi.org/10.1186/s10033-021-00674-0.

3. T. HINO, M. TAMURA, Y. TANAKA, W. KOUNO, Y. MAKINO, S. KAWANO, K. MATSUNAGA, *Development of Underwater Laser Cladding and Underwater Laser Seal Welding Techniques for Reactor Components,* Journal of Power and Energy Systems. **3** 51–59 (2009). https://doi.org/10.1299/jpes.3.51.
4. N. Guo, X. Xing, H. Zhao, C. Tan, J. Feng, Z. Deng, *Effect of water depth on weld quality and welding process in underwater fiber laser welding*, Mater Des. **115,** 112–120 (2017). https://doi.org/10.1016/j.matdes.2016.11.044.
5. N. Guo, Y. Fu, X. Xing, Y. Liu, S. Zhao, J. Feng*, Underwater local dry cavity laser welding of 304 stainless steel,* J Mater Process Technol. **260,** 146–155 (2018) https://doi.org/10.1016/j.jmatprotec.2018.05.025.
6. Levy, N.; Simon-Blecher, N.; Ben-Ezra, S.; Yuval, M.; Doniger, T.; Leray, M.; Karako-Lampert, S.; Tarazi, E.; Levy, O. *Evaluating Biodiversity for Coral Reef Reformation and Monitoring on Complex 3D Structures Using Environmental DNA (EDNA) Metabarcoding.* Sci. Total Environ., **856**, 159051 (2023)
7. Wang, Y.; Qiu, L.C.; Chen, S.G.; Liu, Y. 3D *Concrete Printing in Air and under Water: A Comparative Study on the Buildability and Interlayer Adhesion.* Constr. Build. Mater, **411,** 134403 (2024)
8. Ly, O.; Yoris-Nobile, A.I.; Sebaibi, N.; Blanco-Fernandez, E.; Boutouil, M.; Castro-Fresno, D.; Hall, A.E.; Herbert, R.J.H.; Deboucha, W.; Reis, B.; et al. *Optimisation of 3D Printed Concrete for Artificial Reefs: Biofouling and Mechanical Analysis*. Constr. Build. Mater, **272**, 121649 (2021)
9. Fu, Y.; Guo, N.; Wang, G.; Yu, M.; Cheng, Q.; Zhang, D. *Underwater Additive Manufacturing of Ti-6Al-4V Alloy by Laser Metal Deposition: Formability, Gran Growth and Microstructure Evolution*. Mater. Des. , **197**, 109196 (2021)
10. Wang, Z.D.; Sun, G.F.; Lu, Y.; Chen, M.Z.; Lan, H.F.; Bi, K.D.; *Ni, Z.H. High-Performance Ti-6Al-4V with Graded Microstructure and Superior Properties Fabricated by Powder Feeding Underwater Laser Metal Deposition. Surf.* Coat. Technol, **408**, 126778 (2021)
11. B. Li, C. Han, Y. Xie, P.J.D.S. Bartolo, K. Zhou, *Microstructural heterogeneity induced by thermal accumulation in a nickel–aluminium–bronze alloy additively manufactured via directed energy deposition*, CIRP Annals. (2023). https://doi.org/10.1016/j.cirp.2023.04.008
12. T. Murray, S. Thomas, Y. Wu, W. Neil, C. Hutchinson, *Selective laser melting of nickel aluminium bronze*, Addit Manuf. **33** (2020). https://doi.org/10.1016/j.addma.2020.101122.
13. C. Dharmendra, K. Gururaj, K.G. Pradeep, M. Mohammadi, *Characterization of κ-precipitates in wire-arc additive manufactured nickel aluminium bronze: A combined transmission Kikuchi diffraction and atom probe tomography study,* Addit Manuf. **46** (2021). https://doi.org/10.1016/j.addma.2021.102137.
14. C. Dharmendra, K.P. Rice, B.S. Amirkhiz, M. Mohammadi, *Atom probe tomography study of κ-phases in additively manufactured nickel aluminium bronze in as-built and heat-treated conditions,* Mater Des. **202** (2021). https://doi.org/10.1016/j.matdes.2021.109541.