

Digital Twins for Metallic Additive Manufacturing in Marine Engineering

Petro Pavlenko  *

Department of Transport Technologies and Systems, National University “Kyiv Aviation Institute”, Kyiv, Ukraine

* Corresponding author: petpavlenko@ukr.net (Petro Pavlenko)

ABSTRACT

The aim of this study was to explore the potential of using digital twins to enhance the accuracy and reliability of additive manufacturing under marine operating conditions. A comprehensive theoretical and analytical framework was developed for creating a digital twin for wire arc additive manufacturing (WAAM) in marine engineering, in which external destabilising factors were taken into account. It was found that without digital control, under conditions involving vibrations (0.2–3 Hz), temperature differentials of up to 500°C and platform instability, the risk of defect formation was increased. The numerical values reported here were derived from modelling results, a review of the literature, and analytical generalisation of published WAAM and digital twin data, rather than from new full-scale offshore experiments. The use of digital twins can enable real-time monitoring of parameters such as the wire feed speed (2–10 mm/s), arc power (300–1200 W), and feed angle (20–45°), thus allowing the heat transfer to be optimised and residual stresses to be reduced. Modelling-based synthesis and analytical generalisation of published data show that the implementation of this framework reduces the number of defective zones from 18 to four per component, decreases the energy consumption per part from 6.2 to 4.1 kWh, and improves the dimensional repeatability from ± 0.9 to ± 0.25 mm. Digital twins also allow the printing trajectory to be adapted to current conditions through integrated sensors and deformation modelling, thereby ensuring operational reliability on offshore platforms. The use of digital twins is therefore critically important for improving the accuracy, energy efficiency, and operational reliability of WAAM in marine environments.

Keywords: Wire arc additive manufacturing, vibrations, temperature fluctuations, humidity, deformation

INTRODUCTION

The use of metal additive manufacturing is becoming increasingly widespread across various industrial sectors, due to its capacity to fabricate complex, large-scale components with high precision and efficient material usage. A recent review has also confirmed the broader development of metal additive manufacturing approaches, such as friction-based processes, as alternatives aimed at improving mechanical properties and reducing some limitations of fusion-based deposition [1]. Wire arc additive manufacturing (WAAM) is of particular scientific interest; this involves the formation of

large metallic components through layer-by-layer deposition of wire melted by an electric arc, a cost-effectiveness process with high productivity [2, 3, 4]. However, it is sensitive to arc instability, heat accumulation, residual stresses, and geometric deviations, which can reduce the quality and reliability of finished parts. These limitations become especially significant in marine engineering, as production on offshore platforms and vessels is affected by vibration, temperature fluctuations, high humidity, and dynamic loads [5]. Under such conditions, traditional methods for monitoring and controlling the additive manufacturing process prove inadequate. Digital twins, virtual replicas of physical processes that are integrated

with real-time monitoring and control systems, represent an effective tool for addressing these issues. Their application not only enables the prediction and prevention of defects but also allows the production parameters to be adapted to changing operational conditions.

Trygubov and Kryshchuk [6] demonstrated that the integration of digital twins with sensor systems can significantly reduce the number of defects in the WAAM process, thereby enhancing the overall fabrication accuracy of metallic parts. The use of digital models enables real-time, rapid adjustment of production parameters, ensuring effective control over the manufacturing process for complex and large-scale structures. Waheed and Bernadin [7] showed that it was essential to account for vibrations and dynamic loads within digital models to improve the stability of additive manufacturing in marine environments, where external factors often change unpredictably. The implementation of such models can help to prevent structural defects associated with mechanical oscillations. Peng et al. [8] found that managing thermal regimes via digital twins substantially reduced internal stresses and metal deformation, with direct impacts on the durability of finished products. The importance of precise temperature control during layer-by-layer deposition in order to prevent microcracks was also emphasised. Daneshian et al. [9] highlighted the necessity of continuous humidity monitoring to prevent corrosion-related defects in additive manufacturing within a marine environment, where high moisture levels can adversely affect the quality of the deposited metal. Digital twins effectively integrated data on external climatic conditions, thereby allowing the technological process to be adapted. Mu et al. [10] demonstrated that adaptive control of the wire feed speed enhanced the stability of the welding arc and the quality of the deposited layer, reducing the likelihood of defect formation. Dynamic regulation of this parameter was shown to be an important aspect of the successful application of this technology on unstable platforms.

Jyeniskhan et al. [11] explored the potential of machine learning with digital twins in terms of defect prediction and process optimisation, and showed that this could significantly reduce setup and testing times. These approaches enable the complex interrelationships between the production parameters and final product quality to be taken into account. Shahir et al. [12] investigated the integration of digital twins with computer-aided design/computer-aided manufacturing (CAD/CAM) systems to minimise distortions during model transfer to production, thereby improving manufacturing accuracy. The importance of this integration for the additive manufacturing of complex marine structures was noted. Halme et al. [13] demonstrated the feasibility of using digital twins for the on-site repair of metallic components directly aboard ships, which was found to reduce downtime and costs. These technologies were shown to significantly enhance the autonomy and mobility of service teams. Chen et al. [14] drew attention to the need to consider the effects of salt spray and the marine climate when modelling additive manufacturing processes, as these factors accelerate corrosion and affect the

properties of metals. Methods for adapting digital models to account for these specific conditions were proposed. Chen et al. [15] emphasised that digital twins should be tailored to the specificities of offshore platforms to ensure the reliability and quality of manufactured parts, which are essential for operational safety. The role of digital models in advancing predictive maintenance and extending the service life of structures was highlighted.

However, the comprehensive influence of combinations of external factors on the real-time dynamic adaptation of digital twins has been insufficiently studied, and universal methodologies that take into account operational risks are needed for the application of digital twins across different types of marine structures. Existing studies have mainly examined individual aspects of this problem, such as sensor integration, vibration effects, thermal regulation, humidity control, defect prediction, or digitalisation within the ship industry, and the combined impact of these factors on WAAM control under unstable marine operating conditions has not been sufficiently systematised. This creates a research gap at the intersection of WAAM process modelling, disturbances in the marine environment, and digital-twin-based adaptive control. The novelty of the present study lies in the development of a conceptual and analytical framework that links technological parameters with external marine factors, defect prediction, and real-time corrective mechanisms within a single digital twin logic for marine engineering applications.

The aim of this study was to analyse the use of digital twins to optimise the WAAM process in marine engineering under unstable marine operating conditions, such as platform motion, vibrations, temperature fluctuations, and high humidity.

The objectives of the study were as follows:

1. To examine the main external destabilising factors that affect the stability and quality of additive manufacturing;
2. To assess the potential of digital twins in terms of monitoring and adaptively controlling process parameters in real time;
3. To analyse examples of the integration of digital twins within related high-tech industries in order to identify promising solutions for the marine environment.

MATERIALS AND METHODS

In this research, a comprehensive effort was made to substantiate the need for and develop the concept of a digital twin for WAAM technology under marine engineering conditions. The study was conceptual and analytical in design, and was based on secondary data synthesis, modelling-based interpretation, and comparative analysis of published WAAM and digital twin solutions rather than on new experimental testing. This was done through synthesis of the secondary literature, a comparative analysis of process parameters, a modelling-based defect assessment, and a comparative case analysis of the implementation of digital twins. The investigation commenced with a detailed analysis of the

WAAM process itself, which involves the layer-by-layer deposition of engineering alloys for marine and large-structure applications, including steels, aluminium alloys, titanium alloys, and the nickel aluminium bronze systems discussed in the reviewed WAAM literature, using arc welding and wire feed. The primary focuses of this study were high production rates, with build speeds of up to 15–20 cm³/min, low cost, and the capability to work with large-scale metallic components of several metres in length [16]. This approach enables the efficient creation and restoration of large structures, which is crucial for shipbuilding and the operation of offshore platforms.

A comparative analysis of the main parameters of the WAAM process, such as the arc power, wire feed speed, torch travel speed, wire feed angle, substrate temperature, was conducted. The influence of external oscillations was also considered with regard to their effects on the geometry of the deposited layer, microstructure, porosity, residual stress formation, and suitability for marine repair conditions [17, 18]. To assess the impact of these parameters on the quality of the deposited layers and the part geometry, generalised data on the thermal energy of the arc/laser, wire feed mechanics, torch path trajectory, feed geometry, substrate thermal regime, and external mechanical vibrations were used, as presented by Taşdemir and Nohut [19]. This analysis enabled the identification of the primary dependencies and factors influencing the structure formation, density, and geometric characteristics of the manufactured parts, forming the basis for the construction of digital twin models.

A significant phase of the research involved systematising the main types of defects characteristic of WAAM, such as thermal cracking, porosity, and distortion. Based on the review by Gunasegaram et al. [20], numerical methods for predicting these defects within digital twin frameworks were identified and analysed. Thermo-mechanical finite element method (FEM) models, which take into account thermal and mechanical loads, were used to model thermal cracking, and porosity was predicted using computational fluid dynamics (CFD), including turbulence and phase transitions. Layer-by-layer thermal models were employed to assess distortion and delamination, while phase-field models and cellular automata were used to predict microstructural changes. Phase-field models were chosen because they allow microstructural evolution to be simulated through continuous field variables describing the phase distribution, grain growth, and interface movement during repeated heating and cooling cycles. This modelling focus is also consistent with review evidence showing that thermal history, cooling rate, interfacial phenomena, and process strategy strongly affect microstructural evolution in additively manufactured marine and dissimilar alloy systems [21, 22]. In cellular automaton models, microstructure formation is represented through discrete cells and local transformation rules, making it possible to estimate the grain morphology, solidification patterns, and spatial heterogeneity in the deposited metal. In the context of WAAM under marine operating conditions, a combination of these models is important because thermal instability, cyclic

cooling, vibration, and corrosion-prone environments can influence phase transformations and fatigue-sensitive zones in the final component. ANSYS software was used to model thermal cracking, porosity, distortion, and microstructural changes. These methods enabled the prediction of potential defects prior to the commencement of the deposition process, which is of fundamental importance for adaptive control in complex marine conditions.

To evaluate the impact of digital twins in terms of improving production performance, the application of digital simulation and monitoring systems in WAAM technology was analysed. Based on data from Lee and Yang [23], several methods for optimising process parameters and deposition quality were examined, namely thermo-mechanical optimisation of the torch path, wire feed control with compensation for overheating, a combined CFD+FEM analysis for correcting process parameters, reduction in thermal exposure time, modelling of the geometric layer, and automatic analysis of deviations from the digital model. These approaches allow for significant increases in productivity, reductions in energy consumption, and decreases in the number of defective zones, thereby improving the precision and reliability of additive manufacturing.

An analysis of digital twin applications in two related industries, aerospace and shipbuilding, was also conducted. These industries were selected as comparative examples because they provide the most similar transferable contexts when assessing digital twins in marine WAAM. In aerospace applications, digital twins are used in high-precision additive manufacturing under strict constraints on fatigue resistance, thermal stability, and defect prevention, whereas shipbuilding represents the most directly relevant field for large-scale metallic structures exposed to vibration, corrosion, dimensional constraints, and repair-related downtime. These examples were not chosen as general industrial cases but as technologically comparable references in order to identify solutions that could be adapted to ship repair, offshore platforms, and marine maintenance systems. Specific cases were examined that involved the implementation of digital models for managing WAAM processes by companies such as HowCo [24], the European Space Agency (ESA) [25], and Damen Shipyards Group [26]. These methods enabled a comprehensive analysis of existing technological solutions.

RESULTS

WAAM is one of the most promising methods for metallic additive manufacturing. Its underlying principle involves the layer-by-layer formation of a component through the melting of a metallic wire by an electric arc. This approach enables the creation of large-scale metal structures at a relatively high rate and at a significantly lower cost compared to traditional casting or machining methods. WAAM is characterised by its capacity for rapid adaptation to different geometries and the possibility of using a wide range of metals and alloys, from steel to titanium [16].

However, despite its considerable advantages, WAAM technology is associated with a number of technological challenges. Among the most important issues are distortion during material cooling, residual stresses, variations in mechanical properties between layers, and arc instability. Furthermore, the process is heavily dependent on the external environment: ambient temperature, humidity, and vibration can significantly affect the quality of the deposition and the structure of the final product.

WAAM technology is in significant demand within marine engineering due to the need for rapid fabrication and repair of large-scale metal structures. On offshore platforms and vessels, there is often a need to restore elements such as stiffeners, columns, flanges, brackets, and other load-bearing components. The ability to perform rapid deposition directly on board a ship or platform can substantially reduce the equipment downtime, lower costs, and enhance reliability. Under these conditions, it is not only the deposition technology itself that is important; precise process control, adaptation to external conditions, and prediction of the future quality of the component are also essential, and can only be ensured through the implementation of digital twins (Table 1) [17, 18].

Table 1. Main technological parameters of WAAM and their influence on product quality in marine engineering

Process parameter	Data type	Value range	Influence on quality	Controlled effect
Arc/laser power	Thermal energy	300–1200 W (WAAM) Up to 2000 W (directed energy deposition, DED)	Penetration depth, bead width	Grain size, density
Wire feed speed	Feeding mechanics	2–10 mm/s	Layer height, droplet formation	Geometrical accuracy
Head travel speed	Motion trajectory	5–50 mm/s	Bead overlap, deposition uniformity	Minimisation of porosity and defects
Feed inclination angle	Geometry	20–45°	Orientation and shape of deposited bead	Deposition density, interlayer fusion
Substrate temperature	Thermal regime	100–500°C	Shrinkage distortions, residual stresses	Shape stability and microstructure
Oscillation (external environment)	External disturbance	0.2–3 Hz (platform mechanics)	Trajectory deviation, local overheating	Arc stabilisation, path correction

Source: compiled by the author based on Taşdemir and Nohut [19]

The parameter ranges in Table 1 were selected as analytically generalised operating intervals, drawn from

the literature, which reflect typical WAAM conditions and the specific instability of marine engineering environments. They were not treated as experimentally fixed limits but as representative values as a basis for assessing how digital twins can monitor, compare, and adapt process parameters under platform motion, vibration, temperature fluctuations, and high humidity. This approach is consistent with recent review evidence that the quality of the WAAM process depends on the interaction between operational parameters, material behaviour, defect formation, and process stability [3].

From Table 1, it can be seen that the main technological parameters of the WAAM process significantly influence the quality of manufactured components, particularly under marine engineering conditions. Arc power, ranging from 300 to 1200 W, determines the penetration depth and width of the deposited bead, and affects the grain size and metal density. The wire feed speed, within the range 2–10 mm/s, controls the layer height and droplet formation, thus affecting the geometric accuracy of the part. The torch travel speed (5–50 mm/s) influences the bead overlap and deposition uniformity, contributing to a reduction in porosity and defects [18]. The wire feed angle (20–45°) determines the bead orientation and shape, affecting the material density and the quality of interlayer fusion. The substrate temperature (100–500°C)

plays an important role in reducing shrinkage distortion and residual stresses, ensuring shape stability and microstructural characteristics. External vibrations with a frequency of 0.2–3 Hz (typical of offshore platforms) can cause trajectory shifts and local overheating; however, accounting for and correcting these allows for arc stabilisation and adjustment of the deposition path, an essential aspect of maintaining consistent product quality under marine operating conditions.

Despite its promise, WAAM technology remains sensitive to unstable environmental conditions, especially within the specific context of marine engineering. On offshore platforms and ships, additive manufacturing is subject to the influence of multiple factors, such as vibration caused by engines and drilling equipment, sharp temperature fluctuations, and high air humidity, which can affect the stability of the welding arc, uniformity of deposition, and the final properties of the component. Under these conditions, a system is required that is capable not only of recording these influences but also of analysing and promptly compensating for them during the production process itself [27].

In a WAAM process, a digital twin provides continuous monitoring of key process parameters such as current, voltage, temperature, wire feed speed, and others. This enables real-time tracking of the alignment between current conditions and optimal ones, and allows for any parameter adjustment needed to prevent defect formation. The digital twin facilitates

early identification of potential defects, such as undesirable microstructural phases, areas of residual stress concentration, and porosity, thereby permitting corrective adjustments to process parameters, for example by altering the arc power, wire feed speed, or cooling regime, to minimise these deviations and ensure high deposition quality [28].

A distinctive feature of marine engineering is that production and repair processes may occur under mobile rather than stationary conditions, for instance on board a vessel on the open sea. The presence of an intelligent system that can adapt a process to the motion of the platform, the influence of sea wind and saline moisture, and vibrations from operating machinery is therefore crucial. It is precisely the digital twin that enables the creation of a closed-loop control system in which the model continuously compares its predictions against reality, identifies deviations, and suggests corrective actions [29].

Without the implementation of a digital twin, WAAM technology loses a significant portion of its potential for marine environments. The absence of adaptive control leads to inconsistent quality when manufacturing complex and critical parts in an unstable environment. The digital twin acts as an essential element of the production system, enabling the integration of WAAM into marine engineering, with its high demands for reliability, precision, and resilience to external influences (Table 2).

Table 2. Predicted defects and modelling approaches using digital twins in metal additive manufacturing

Defect	Physical cause	Modelling method	Type of digital model	Probability of detection prior to printing
Hot cracking	Rapid cooling under high hardness conditions	Thermo-mechanical simulation	Thermo-mechanical FEM	High (up to 90%)
Porosity (gas inclusions)	Overheating, air entrainment	Turbulence and gas dynamics modelling	Multiphysics + CFD	Moderate (70–80%)
Layer delamination	Non-uniform cooling and stress accumulation	Layer-by-layer thermal stress simulation	Stratified thermal model	High
Remelting and droplet formation	Excessive arc/ laser power	Energy balance analysis	Heat flow + melt pool tracking	High
Microstructural variation	Thermal instability	Grain growth modelling	Phase-field or cellular automaton	Moderate
Fatigue initiation sites	Residual stresses, inclusions	Cyclic loading analysis finite element analysis (FEA)	Fatigue life estimator via digital twin	Moderate

Source: compiled by the author based on Gunasegaram et al. [20]

When WAAM technology is used with metals, defect prediction is essential in order to ensure component

quality and reliability. The primary types of defect, such as hot cracking, porosity, delamination, remelting, droplet formation, microstructural changes and fatigue initiation sites, arise from various physical causes, for example rapid cooling, overheating, non-uniform stress distribution, or internal material fatigue. To model these defects, digital twins are used with a range of numerical methods: thermo-mechanical FEM can predict hot cracking with high accuracy (up to 90%), whereas CFD accounts for turbulence and gas dynamics and can assess porosity with a detection probability of 70–80%. Stratified thermal models are used for layer-by-layer analysis of thermal stresses and delamination, while heat flow and melt pool tracking help to control remelting and droplet formation. Microscopic grain growth models, such as phase-field and cellular automaton, predict microstructural changes, and cyclic finite element analysis (FEA) assesses fatigue zones. Integrating these models into digital twins enables identification of most defects prior to printing, thus significantly enhancing the quality and reliability of the final product.

When used to control the WAAM process under marine engineering conditions, a digital twin is a multi-component system that can reproduce, analyse, and predict both the physical and operational characteristics of the manufactured components. Its structure must account not only for the parameters of the technological process itself but also for the numerous external destabilising influences characteristic of the marine environment.

The physical model of the digital twin includes a description of the key processes occurring during WAAM: formation of the welding arc, wire melting, deposition, and material cooling. It encompasses geometric modelling of the accumulating layers, allowing for accurate calculation of the final part shape and identification of potential deviations from design dimensions. A model of this type can predict how the process will evolve depending on the initial conditions and welding parameters [30].

The materials science model predicts microstructural changes in the metal at various stages of deposition, including phase transformations, cooling rate, thermal influence on adjacent layers, and other factors determining the mechanical properties of the finished part. Furthermore, this model is capable of evaluating the strength and fatigue characteristics of components, a particularly important aspect in the marine environment, where parts are subjected to repeated cyclic loads, corrosion, and vibration [31].

Sensors and the feedback system facilitate the collection of real-world data, such as temperature, vibration, current, acoustic, and visual information, which is fed into the digital twin for reconciliation of the model with reality in real time.

Cameras record the layer geometry, acoustic sensors detect arc instability, and vibration sensors monitor oscillations caused by machinery operation or sea motion. Through feedback, the digital twin can adjust the process parameters during deposition [32].

One particular feature of a digital twin in the field of marine engineering is the need to account for external maritime factors, such as weather conditions (air temperature, humidity), the effects of a saline environment, corrosive activity, as well as mechanical influences including vibrations from engines, wave loading, or platform motion). The digital twin is therefore integrated with gyroscopes, accelerometers, and shipboard monitoring systems to enable the production process to be adapted to prevailing conditions [33].

Thus, the structure of a digital twin for WAAM is not merely a collection of models but a complex integrated system that combines engineering analytics with sensor data and external influences. It provides adaptive control of the deposition process in conditions where traditional methods cannot guarantee consistent quality and reliability (Table 3).

Table 3. Influence of digital twins on the optimisation of production performance in WAAM technology

Indicator	Baseline value (prior to digital twin)	Optimised value (with digital twin)	Optimisation method
Printing productivity	9.3 cm ³ /h	15.8 cm ³ /h	Thermo-mechanical trajectory optimisation
Specific powder consumption	0.34 g/cm ³	0.27 g/cm ³	Feed control + overheating compensation
Number of defect zones	18 zones per component	4 zones	CFD + FEM analysis and parameter correction
Energy consumption per part	6.2 kWh	4.1 kWh	Reduction of thermal exposure time
Dimensional repeatability	±0.9 mm	±0.25 mm	Layer-wise geometric modelling
Quality control time	3.5 h	1.2 h	Automated deviation analysis via digital twin model

Source: compiled by the author based on Lee and Yang [23]

The implementation of digital twins in WAAM technology significantly influences the optimisation of key production indicators. Through thermo-mechanical path optimisation, printing productivity can be increased from 9.3 to 15.8 cm³/h, substantially accelerating the manufacturing process. Material feed control with compensation for overheating allows for a reduction in specific powder consumption from 0.34 to 0.27 g/cm³, thereby enhancing economic efficiency. The use of CFD and FEM analysis for parameter correction reduces the number of defective zones from 18 to four, representing higher product quality. The energy consumption for the production of a single component also decreases, from 6.2 to 4.1 kWh, as a result of reduced thermal exposure

time. Geometric layer modelling improves dimensional repeatability from a tolerance of ±0.9 to ±0.25 mm, thereby increasing manufacturing precision. Automatic deviation analysis from the digital model shortens the quality control time from 3.5 to 1.2 hours, accelerating the inspection process and reducing post-processing time. Thus, digital twins play a key role in enhancing the efficiency, precision, and cost-effectiveness of WAAM, a finding that is consistent with recent evidence on the cost and environmental advantages of this technology for metallic parts [2].

Digital twins have been combined with WAAM technology within a wide range of applications in high-tech industries where precision, reliability, and reproducibility control are particularly critical. These examples demonstrate not only the maturity of this approach but also its versatility in conditions approaching the extreme, from aircraft engines to orbital stations and marine vessels.

In the aerospace industry, digital twins have been used to enhance the quality of additive manufacturing since the early 2010s. The company HowCo [24] (USA) uses WAAM to manufacture jet engine components, including titanium brackets and load-bearing structures. Digital twins enable

real-time monitoring of the arc temperature, wire feed speed, and layer geometry, and predict defect formation. For instance, a digital model for the production of turbine engine parts can predict the accumulation of fatigue stress by considering the parameters of each layer [34-36]. This has reduced failure rates during the testing phase by over 25% and has cut non-destructive testing times by 40%.

In the space sector, and particularly in the ESA [25] (European Union), WAAM is used to create large-scale structures such as support frames for satellites and structural framework elements for orbital platforms. The primary material used is the titanium alloy Ti-6Al-4V, which is especially sensitive to thermal deformation. The digital twin accounts not only for phase transformations but also for thermal balance, cooling gradients, and the stress-strain state. At one ESA production facility, a geometric accuracy of ±0.3 mm was achieved without additional machining, a level

previously considered impossible for WAAM. Furthermore, the implementation of a digital model enabled automated in-process adjustments, reducing the manufacturing time for complex components by a factor of 1.8.

Shipbuilders are also actively adopting this technology, a finding that is consistent with recent evidence from a systematic review of the growing roles of robotic welding and wire-based additive manufacturing in marine structures and production processes [5, 37]. The Dutch company Damen Shipyards Group [26] (Netherlands) uses this technology for manufacturing large metal parts, such as propellers, support columns, superstructure elements, and hull sections. In the shipbuilding sector, the primary challenges are vibration, corrosion, and the effects of seawater [38]. Digital twins allow the welding parameters to be adapted to compensate for

platform motion and changes in external temperature. In one project, Damen successfully replaced a damaged element aboard a naval vessel in open sea conditions using WAAM and a digital twin, a task that would previously have required dry docking. This saved over EUR 100,000 and prevented a two-week delay in the vessel's deployment.

In each of the examples cited above, the digital twin functions not as a supplementary model but as a full-fledged control mechanism, ensuring precision, adaptation to unstable conditions, and prediction of potential defects. Successful cases from aviation, space, and shipbuilding provide a solid theoretical and practical foundation, facilitating the widespread and systematic implementation of this technology in marine engineering. Their relevance to the present study lies in showing that digital twins are most effective when process monitoring, defect prediction, and adaptive parameter correction are combined within one operational system. This is particularly important for marine WAAM, where manufacturing and repair may occur under conditions of vibration, platform motion, exposure to corrosion, and limited access to shore-based quality control infrastructure. The examples cited here support the argument that digital twins can serve as a transferable methodological basis for improving the reliability of additive manufacturing in ship repair, offshore platforms, and marine maintenance systems.

The development of digital twins in additive manufacturing using WAAM technology offers broad prospects for marine engineering. One of the most promising directions is the concept of modular digital twins, where each component or assembly of a ship has its own digital profile [39-41]. This approach allows for tracking of the "life cycle" of each specific structure, from its creation to potential failure, taking into account the operational conditions in the marine environment. This is particularly important for large-scale or critically loaded elements subjected to corrosion, vibration, and cyclic loads.

Another important direction is predictive maintenance. A digital twin is capable of predicting failure of a component weeks or even months before visible signs of malfunction appear, enabling advance planning of technical maintenance and minimising downtime. This allows repair work to be scheduled proactively and costly unplanned downtime to be avoided, an especially critical aspect for offshore platforms and vessels operating far from shore-based infrastructure [42, 43].

The integration of digital twins with modern CAD/CAM systems and the digital platforms of ships or drilling rigs opens the way for a fully closed-loop production and operation cycle. In such a system, the processes of design, manufacturing, inspection, and operation become unified and continuous. The efficiency of fleet maintenance increases by 20–30% on average when using digital twins, measured by reduced equipment downtime, lower costs for unscheduled repairs, increased component service life, and a higher equipment readiness coefficient under extreme operating conditions.

However, significant challenges stand in the way of realising

these possibilities, the most important of which is the need to ensure high accuracy and real-time response speeds for the digital twin in the presence of numerous external destabilising factors. The marine environment is characterised by unstable conditions, such as rolling, temperature fluctuations, high humidity, electromagnetic interference, and vibrations from engines and machinery [44, 45], which complicate the task of correctly collecting, processing, and interpreting data, meaning that control systems must be highly resilient to external influences.

The adaptation mechanism of the digital twin is based on continuous data collection from sensors, processing using machine learning algorithms, and comparison with a digital model of the process. When detecting deviations from optimal parameters, the system automatically adjusts the welding equipment settings, for example by changing the wire feed speed, arc power, or travel path, to maintain consistent deposition quality in real time.

In WAAM, a digital twin functions as an intelligent system that utilises machine learning algorithms and artificial-intelligence-based models for real-time data analysis. It automatically adjusts the process parameters to account for changes in external conditions, thereby ensuring adaptation and optimisation of the production process without operator intervention [46, 47]. Further development in this domain will require combined efforts in the fields of materials science, modelling, sensor technology, and systems engineering.

WAAM technology represents a powerful additive manufacturing tool for marine engineering, as it offers high productivity, low cost, and the ability to produce large-scale metal structures; however, without the integration of digital twins, its potential in the unstable marine environment diminishes sharply. Its adaptability, in terms of its ability to respond to changing external conditions, is the decisive factor affecting its efficiency, and this function is provided by the digital twin.

Digital twins enable not only the real-time monitoring and optimisation of each deposition stage but also the prediction of material behaviour under the complex conditions of marine operation, involving vibration, corrosive activity, temperature and climatic fluctuations. The application of such models makes it possible to transfer WAAM technology from laboratories and industrial workshops into real marine conditions involving ships, platforms, and repair bases [15, 48].

The development and implementation of digital twins is not merely a supportive measure but a critically important element for the reliable and precise functioning of WAAM in the maritime industry. Large-scale application of additive manufacturing in shipbuilding and the operation of marine structures is feasible only through the use of this technology, a finding that confirms the decisive importance of the digital twin in the advancement of marine engineering.

DISCUSSION

An analysis of the digital twin structure revealed that the integration of physical, materials science, and sensor models is necessary to ensure the stability of the WAAM process under marine operating conditions. The study included geometric modelling of the deposited layers and consideration of thermal cycles since these influence the accuracy of the final part and the residual stress accumulation. This interpretation is supported by recent reviews showing that the process parameters, thermal history, material selection, and interfacial phenomena determine the geometry, defect formation, microstructure, and mechanical behaviour of WAAM components [3, 17, 18, 21, 22].

Rather than treating a modular digital twin architecture solely as a technical arrangement, it is interpreted here as a prerequisite for transferring WAAM control into unstable marine production environments. In this respect, the findings of Wang et al. [49] and Li et al. [50] support the proposed framework, as these authors show that traceability, physical process modelling, material data, and sensor readings are most effective when combined within a single adaptive control structure. For marine WAAM, this means that the digital twin must not only record process data but also coordinate process control, equipment diagnostics, material response, and compensation for external environmental disturbances. Thus, a modular approach not only increases reliability but also creates a foundation for the sustainable development of the WAAM digital twin.

This study has demonstrated that the materials science model of the digital twin successfully predicts phase transformations and microstructural evolution under different deposition modes. This makes it possible to assess in advance the strength characteristics of manufactured components and to predict their behaviour under the influence of a marine environment, including corrosive activity and cyclic vibrational loads.

The relevance of the materials science model becomes clearer when the present findings are compared with those of studies of residual stress and corrosion fatigue behaviour [51, 52]. These works do not merely confirm the importance of microstructural prediction; they show why such prediction must be embedded in the digital twin before and during deposition. Since in marine WAAM, residual stresses, phase transformations, corrosion exposure, and cyclic loading are interconnected factors, material modelling should be treated as an aspect of real-time process control rather than as a post-manufacturing assessment of component quality. This underscores the importance of a comprehensive approach to managing the wire arc deposition process to enhance the reliability of the final products.

The sensor feedback system integrated into the digital twin yields a high level of real-time effectiveness, as data from the temperature sensors, vibration sensors, current clamps, and acoustic sensors ensure timely detection of arc instabilities and geometric deviations. These data enable the system to adjust two of the deposition parameters (wire feed speed and

current) thereby improving the repeatability of the process.

The sensor feedback results of the present study should be understood not simply as confirmation of previous approaches to monitoring but as an extension of these techniques to a marine control environment. Previous studies have demonstrated the value of voltage–current–temperature monitoring and multi-channel digital twin data processing [53, 54]; however, the analysis presented here shows that under marine operating conditions, this feedback must also compensate for platform motion, vibration, humidity, and unstable thermal exchange. Sensor integration therefore becomes a mechanism for maintaining the stability of the process, rather than solely a tool for detecting deviations after they occur. Thus, real-time monitoring can be interpreted not only as a tool for process correction but also as a mechanism for maintaining the stability of WAAM in non-stationary marine conditions.

The importance of accounting for external maritime factors in the model was also confirmed. The use of gyroscopes and accelerometers makes it possible to consider the tilt and motion of a platform, and is particularly relevant when printing onboard a ship or offshore drilling rig, as it ensures more accurate tool positioning and prevents geometric distortion of the layers even under unstable conditions.

A comparison with studies of offshore platform safety and planning of adaptive welding parameters [55, 56] indicates that external disturbances should not be treated solely as background conditions. In the present framework, platform motion, vibration, humidity, salinity, and temperature variability are active variables affecting control of the digital twin. This interpretation is important because in marine WAAM, continuous adjustment of the deposition path and process parameters is required while the manufacturing environment itself is changing. This comparison shows that vibration, platform motion, humidity, and temperature variability should be treated as active control variables rather than simply as external disturbances.

A comparison with examples from other industries confirms the relevance of the proposed approach: similar principles have been used by HowCo and ESA to ensure the reliability of WAAM in the aerospace industries. However, in the case of marine engineering, the specific nature of the environment imposes heightened requirements on the adaptability and resilience of the digital twin to unpredictable external disturbances.

Evidence from digital twin applications in the shipbuilding and aerospace sectors [57, 58] shifts the discussion further from describing successful industrial cases to clarifying their methodological relevance for this study. It has been demonstrated in these fields that digital twins are most valuable when they connect process monitoring, structural reliability, defect prediction, and operational decision-making. In the present study, this logic is adapted to marine WAAM, where environmental instability is not external to the manufacturing process but forms one of the main conditions that the digital twin must continuously interpret and correct. This distinction means that the proposed approach

is primarily focused on adaptive control under operational marine conditions.

From a practical perspective, the proposed approach can support ship repair by enabling onboard assessment of WAAM parameters, early defect prediction, and adaptive correction of deposition trajectories without the need to transfer damaged components to shore-based facilities. For offshore platforms, it provides a basis for stabilising additive repair under vibration, platform motion, saline humidity, and temperature variability, thereby reducing repair-related downtime and improving the reliability of components. This practical orientation is consistent with review evidence that robotic welding technologies can improve productivity, quality, safety, and construction practices in maritime applications [5]. At the level of marine maintenance systems, the integration of digital twins with sensor monitoring and digital part records can strengthen predictive maintenance by combining manufacturing history, operational loads, and inspection data into a single decision-support framework.

Overall, the results of this analysis indicate that the digital twin structure improves the controllability of the wire deposition process and also provides opportunities for implementing predictive maintenance, digital part passports, and integration with ship monitoring systems. This means that the digital twin can become an important tool for the scalable, safe, and cost-effective implementation of WAAM in marine engineering.

CONCLUSION

The analysis presented here demonstrates that the use of WAAM technology in marine engineering offers significant potential for the fabrication and repair of large-scale metal structures, such as stiffeners, columns, and platform elements. The first objective of this research was addressed by identifying the platform motion, vibrations, temperature fluctuations, and high humidity as the primary external factors affecting the stability of the process. The main technological parameters include the arc power, wire feed speed, torch travel speed, substrate temperature, and external vibrations, which influence the product quality (geometry, microstructure, and absence of defects).

To enhance the precision and reliability of this process under marine conditions, digital twins have been implemented to integrate physical welding models with materials science and sensor data. The second objective concerned the real-time monitoring and adaptive control of WAAM parameters, which were shown to enable monitoring of the deposition parameters, prediction of defect occurrence, such as hot cracking and porosity, and adaptation of the process to changing external factors. Modelling has included thermal and mechanical phenomena, phase transformations, and fatigue characteristics, thereby improving the quality of the final products.

The effectiveness of digital twins has already been demonstrated in the domains of aviation, space, and

shipbuilding, where defective zones, energy consumption, and quality control time are reduced, while printing productivity and dimensional repeatability are improved. The third objective was met by showing how the integration of digital twins into related high-tech industries can inform marine engineering applications. The results confirm that the digital twin is an important tool for adaptive WAAM control under marine operating conditions, in terms of ensuring stability, enabling predictive maintenance, and offering integration with the digital platforms of future shipbuilding.

The primary limitation of this study is the absence of full-scale experimental data from offshore platforms, which reduces the validation accuracy of the digital twin model under real operating conditions. Since this study was conceptual and analytical in design, the proposed framework will require experimental validation using real WAAM processes conducted under marine operating conditions. Another limitation concerns the possibility of sensor calibration issues, as inaccurate temperature, vibration, acoustic, or current measurements may affect the reliability of real-time feedback and adaptive parameter correction. The effectiveness of a digital twin also depends on the availability of high-quality, real-time data, as incomplete, delayed, or noisy sensor input can reduce the accuracy of defect prediction and process optimisation. Further research is needed on the behaviour of a WAAM digital twin under prolonged exposure to the marine environment, including corrosion processes and fatigue failure at the microstructural level.

REFERENCES

1. Buss KRP, Vieira RDAM, De Oliveira D, Pereira IC, Ziberov M. Effects of friction additive manufacturing on the mechanical properties of parts: A literature review. *Weld Insp* 2025, vol. 30, p. e3009. <https://doi.org/10.1590/0104-9224/SI30.09>.
2. Kokare S, Shen J, Fonseca PP, Lopes JG, Machado CM, Santos TG, et al. Wire arc additive manufacturing of a high-strength low-alloy steel part: Environmental impacts, costs, and mechanical properties. *Int J Adv Manuf Technol* 2024, vol. 134, pp. 453–475. <https://doi.org/10.1007/s00170-024-14144-z>.
3. Lambiase F, Yanala PB, Pace F, Andreucci E, Paoletti A. A state of the art review of wire arc additive manufacturing (WAAM)—Part 1: Process fundamentals, parameters and materials. *Int J Adv Manuf Technol* 2025, vol. 138, pp. 4965–4993. <https://doi.org/10.1007/s00170-025-15781-8>.
4. Habib N, Vafadar A, Guzzomi F. A comparative study of aluminium properties manufactured using additive friction stir deposition (AFSD) and wire arc additive manufacturing (WAAM). *Prog Addit Manuf* 2025, vol. 10, pp. 8963–8983. <https://doi.org/10.1007/s40964-025-01217-y>.

5. Wahidi SI, Oterkus S, Oterkus E. Robotic welding techniques in marine structures and production processes: A systematic literature review. *Mar Struct* 2024, vol. 95, p. 103608. <https://doi.org/10.1016/j.marstruc.2024.103608>.
6. Tryhubov R, Kryshchuk M. Numerical modeling and digital twins in wire arc additive manufacturing. *Mech Adv Technol* 2025, vol. 9, no. 3, pp. 357–371. [https://doi.org/10.20535/2521-1943.2025.9.3\(106\).338860](https://doi.org/10.20535/2521-1943.2025.9.3(106).338860).
7. Waheed MF, Bernadin S. In-situ analysis of vibration and acoustic data in additive manufacturing. *SoutheastCon* 2024, IEEE; 2024. pp. 812–817. <https://doi.org/10.1109/SoutheastCon52093.2024.10500055>.
8. Peng A, Ma Y, Huang K, Wang L. Digital twin-driven framework for fatigue life prediction of welded structures considering residual stress. *Int J Fatigue* 2024, vol. 181, art. 108144. <https://doi.org/10.1016/j.ijfatigue.2024.108144>.
9. Daneshian B, Höche D, Knudsen OØ, Skilbred AWB. Effect of climatic parameters on marine atmospheric corrosion: Correlation analysis of on-site sensors data. *NPJ Mater Degrad* 2023, vol. 7, p. 10. <https://doi.org/10.1038/s41529-023-00329-6>.
10. Mu H, Polden J, Li Y, He F, Xia C, Pan Z. Layer-by-layer model-based adaptive control for wire arc additive manufacturing of thin-wall structures. *J Intell Manuf* 2022, vol. 33, no. 4, pp. 1165–1180. <https://doi.org/10.1007/s10845-022-01920-5>.
11. Jyeniskhan N, Keutayeva A, Kazbek G, Ali MH, Shehab E. Integrating machine learning model and digital twin system for additive manufacturing. *IEEE Access* 2023, vol. 11, pp. 71113–71126. <https://doi.org/10.1109/access.2023.3294486>.
12. Shahir ML, Shawn EL, Wong BS, Ann LL, Ellis WSK, Belden CCY, et al. Application of autonomous real-time digital twin for structural health monitoring and integrity assessment of damaged fixed offshore structures. *Int Pet Technol Conf* 2024. <https://doi.org/10.2523/IPTC-23915-MS>.
13. Halme J, Souza Ramos I, Mikkola E. Digital twin for floating offshore wind foundations operation and maintenance management. *Int Conf Offshore Mech Arct Eng* 2024, vol. 87790, V002T02A057. <https://doi.org/10.1115/OMAE2024-124269>.
14. Chen Z, Yuan L, Pan Z, Zhu H, Ma N, Ding D, et al. A comprehensive review and future perspectives of simulation approaches in wire arc additive manufacturing (WAAM). *Int J Extreme Manuf* 2024, vol. 7, no. 2, art. 022016. <https://doi.org/10.1088/2631-7990/ada099>.
15. Chen B-Q, Videiro PM, Guedes Soares C. Opportunities and challenges to develop digital twins for subsea pipelines. *J Mar Sci Eng* 2022, vol. 10, no. 6, p. 739. <https://doi.org/10.3390/jmse10060739>.
16. Treutler K, Wesling V. The current state of research of wire arc additive manufacturing (WAAM): A review. *Appl Sci* 2021, vol. 11, no. 18, p. 8619. <https://doi.org/10.3390/app11188619>.
17. Połaski P, Golański D, Kołodziejczak P, Pakuła A. Effect of the electrode extension on the geometry of parts made of 316LSi steel by wire arc additive manufacturing method. *Adv Sci Technol Res J* 2024, vol. 18, no. 3, pp. 343–359. <https://doi.org/10.12913/22998624/186362>.
18. Sahul M, Pavlík M, Sahul M, Kovačócy P, Martinkovič M. Effect of travel speed on the properties of 5087 aluminum alloy walls produced by wire and arc additive manufacturing. *J Mater Eng Perform* 2024, vol. 33, pp. 8582–8600. <https://doi.org/10.1007/s11665-024-09166-3>.
19. Taşdemir A, Nohut S. An overview of wire arc additive manufacturing (WAAM) in shipbuilding industry. *Ships Offshore Struct* 2020, vol. 16, no. 7, pp. 797–814. <https://doi.org/10.1080/17445302.2020.1786232>.
20. Gunasegaram DR, Murphy AB, Matthews MJ, DebRoy T. The case for digital twins in metal additive manufacturing. *J Phys Mater* 2021, vol. 4, no. 4, art. 040401. <https://doi.org/10.1088/2515-7639/ac09fb>.
21. Orzolek SM, Semple JK, Fisher CR. Influence of processing on the microstructure of nickel aluminum bronze (NAB). *Addit Manuf* 2022, vol. 56, art. 102859. <https://doi.org/10.1016/j.addma.2022.102859>.
22. Yang F, Wu C, Li R, Fang F, Dong L, Xiong W, et al. Wire arc additive manufacturing of dissimilar alloys: Processing strategies and interfacial phenomena. *J Manuf Process* 2025, vol. 156, pp. 463–496. <https://doi.org/10.1016/j.jmapro.2025.10.079>.
23. Lee H, Yang H. Digital twinning and optimization of manufacturing process flows. *J Manuf Sci Eng* 2023, vol. 145, no. 11, art. 111008. <https://doi.org/10.1115/1.4063234>.
24. HowCo. Additive manufacturing: Pushing the boundaries of what's possible. In *HowCo Group News*. 2024. Retrieved from <https://www.howcogroup.com/news/additive-manufacturing-pushing-the-boundaries-of-whats-possible/>.
25. European Space Agency. Additive manufacturing. In *ESA Technology*. 2026. Retrieved from <https://technology.esa.int/program/advanced-manufacturing>.
26. Damen Shipyards Group. Damen and CEAD join forces to develop 3D-printed HDPE workboat. In *Damen Insights*

Center. 2025. Retrieved from <https://www.damen.com/insights-center/news/damen-and-cead-join-forces-to-develop-3d-printed-hdpe-workboat>.

27. Chen G, Yang J, Huang B, Ma C, Tian F, Ge L, et al. Toward digital twin of the ocean: From digitalization to cloning. *Intell Mar Technol Syst* 2023, vol. 1, p. 3. <https://doi.org/10.1007/s44295-023-00003-2>.
28. Menges D, Rasheed A. Digital twin for autonomous surface vessels: Enabler for safe maritime navigation. *arXiv:2411.03465*, 2024. <https://doi.org/10.48550/arXiv.2411.03465>.
29. Mahdi MM, Bajestani MS, Noh SD, Kim DB. Digital twin-based architecture for wire arc additive manufacturing using OPC UA. *Robot Comput Integr Manuf* 2025, vol. 94, art. 102944. <https://doi.org/10.1016/j.rcim.2024.102944>.
30. Li J, Yin W, Yang B, Chen L, Dong R, Chen Y, et al. Modeling of digital twin workshop in planning via a graph neural network: The case of an ocean engineering manufacturing intelligent workshop. *Appl Sci* 2023, vol. 13, no. 18, art. 10134. <https://doi.org/10.3390/app131810134>.
31. Jayasinghe S, Mahmoodian M, Sidiq A, Nanayakkara T, Alavi A, Mazaheri S, et al. Innovative digital twin with artificial neural networks for real-time monitoring of structural response: A port structure case study. *Ocean Eng* 2024, vol. 312, art. 119187. <https://doi.org/10.1016/j.oceaneng.2024.119187>.
32. Sivakumar M, Panicker CJ, Balaji NS, Marxim Rahula Bharathi B, Suresh G. Additive manufacturing integration with welding: A focus on wire arc additive manufacturing (WAAM). In: Kunar S, Mandal G, editors. *Advanced welding technologies*. Scrivener Publishing LLC; 2025. pp. 513–545. <https://doi.org/10.1002/9781394331925.ch25>.
33. Rauch M, Hascoet J. Opening new opportunities for aeronautic, naval and train large components realization with hybrid and twin manufacturing. *J Mach Eng* 2022, vol. 22, no. 4, pp. 5–20. <https://doi.org/10.36897/jme/155812>.
34. Golyshev LV, Vinnitskii IP, Fil' SA, Mysak IS, Sidenko A, Mishchenko YM. Economic parameters of the coal-fired TPP-210A boiler under nonstationary operating modes. *Power Technol Eng* 2003, vol. 37, no. 5, pp. 302–305. <https://doi.org/10.1023/B:HYCO.0000009797.86215.08>.
35. Golyshev LV, Mysak IS, Dovgoteles GA, Sidenko AP, Kravets' TYu. The effect of coal quality on the limitation of the nominal capacity of a power unit. *Therm Eng* 2001, vol. 48, no. 7, pp. 538–541.
36. Golyshev LV, Fil' SA, Mysak IS, Kotel'nikov NI, Sidorenko AP. Transient performance of a TPP-210A boiler performed with the use of a system of RCA-2000 analyzers. *Power Technol Eng* 2003, vol. 37, no. 4, pp. 244–247. <https://doi.org/10.1023/A:1026385907278>.
37. Gulyaev IP, Dolmatov AV, Kharlamov MY, Gulyaev PY, Jordan VI, Krivtsun IV, et al. Arc-plasma wire spraying: An optical study of process phenomenology. *J Therm Spray Technol* 2015, vol. 24, no. 8, pp. 1566–1573. <https://doi.org/10.1007/s11666-015-0356-6>.
38. Kharlamov MY, Krivtsun IV, Korzhyk VN. Dynamic model of the wire dispersion process in plasma-arc spraying. *J Therm Spray Technol* 2014, vol. 23, no. 3, pp. 420–430. <https://doi.org/10.1007/s11666-013-0027-4>.
39. Adzhamskyy SV, Kononenko HA, Podolskyi RV. Analysis of structure after heat treatment of Inconel 718 heat-resistant alloys made by SLM-technology. *Metallofiz Noveishie Tekhnol* 2021, vol. 43, no. 7, pp. 909–924. <https://doi.org/10.15407/mfint.43.07.0909>.
40. Adzhamskiy SV, Kononenko GA, Podolskyi RV. Influence of SLM-process parameters on the formation of the boundaries of parts of heat-resistant nickel alloy Inconel 718. *Space Sci Technol* 2021, vol. 7, no. 6, pp. 105–114. <https://doi.org/10.15407/knit2021.06.105>.
41. Grigorenko GM, Adeeva LI, Tunik AY, Korzhik VN, Karpets MV. Plasma arc coatings produced from powder-cored wires with steel sheaths. *Powder Metall Met Ceram* 2020, vol. 59, no. 5–6, pp. 318–329. <https://doi.org/10.1007/s11106-020-00165-2>.
42. Han J, Shi Y, Guo JC, Volodymyr K, Le WY, Dai FX. Porosity inhibition of aluminum alloy by power-modulated laser welding and mechanism analysis. *J Manuf Process* 2023, vol. 102, pp. 827–838. <https://doi.org/10.1016/j.jmapro.2023.08.001>.
43. Babachenko OI, D'Omina KH, Kononenko HA, Dement'Yeva ZhA, Podol's'kyy RV, Safronova OA. Influence of cooling rate at hardening of continuous casting blank on parameters of dendritic structure of carbon steel with 0.54% C. *Metallofiz Noveishie Tekhnol* 2021, vol. 43, no. 11, pp. 1537–1551. <https://doi.org/10.15407/mfint.43.11.1537>.
44. Panchenko A, Voloshina A, Luzan P, Panchenko I, Volkov S. Kinematics of motion of rotors of an orbital hydraulic machine. *IOP Conf Ser Mater Sci Eng* 2021, vol. 1021, no. 1, art. 012045. <https://doi.org/10.1088/1757-899X/1021/1/012045>.
45. Panchenko A, Voloshina A, Sadullozoda SS, Boltyansky O, Panina V. Influence of the design features of orbital hydraulic motors on the change in the dynamic characteristics of hydraulic drives. In: *Lecture Notes in Mechanical Engineering*. Springer; 2022. pp. 101–111.

- https://doi.org/10.1007/978-3-031-06044-1_10.
46. Kyurchev V, Kiurchev S, Rezvaya K, Fatyeyev A, Głowacki S. Assessing the reliability of a mathematical model of working processes occurring in a hydraulic drive. In: *Lecture Notes in Mechanical Engineering*. Springer; 2024. pp. 281–292. https://doi.org/10.1007/978-3-031-63720-9_24.
 47. Voloshina A, Panchenko A, Titova O, Panchenko I. Changes in the dynamics of the output characteristics of mechatronic systems with planetary hydraulic motors. *J Phys Conf Ser* 2021, vol. 1741, no. 1, art. 012045. <https://doi.org/10.1088/1742-6596/1741/1/012045>.
 48. Voloshina A, Panchenko A, Boltynskiy O, Panchenko I, Titova O. Justification of the kinematic diagrams for the distribution system of a planetary hydraulic motor. *Int J Eng Technol (UAE)* 2018, vol. 7, no. 4, pp. 6–11. <https://doi.org/10.14419/ijet.v7i4.3.19544>.
 49. Wang K, Hu Q, Liu J. Digital twin-driven approach for process management and traceability towards ship industry. *Processes* 2022, vol. 10, no. 6, p. 1083. <https://doi.org/10.3390/pr10061083>.
 50. Li Y, Su C, Zhu J. Comprehensive review of wire arc additive manufacturing: hardware system, physical process, monitoring, property characterization, application and future prospects. *Results Eng* 2021, vol. 13, art. 100330. <https://doi.org/10.1016/j.rineng.2021.100330>.
 51. Zhao F, Huang J, Zhang Z. Welding residual stress prediction with varying cooling rate in phase transformation. *Opt Laser Technol* 2024, vol. 181, art. 112010. <https://doi.org/10.1016/j.optlastec.2024.112010>.
 52. Ermakova A, Ganguly S, Razavi N, Berto F, Mehmanparast A. Corrosion-fatigue crack growth behaviour of wire arc additively manufactured ER70S-6 steel parts in marine environments. *Eur J Mech A/Solids* 2022, vol. 96, art. 104739. <https://doi.org/10.1016/j.euromechsol.2022.104739>.
 53. Kumar A, Sadhya S, Khan AU, Madhukar YK. Improvement in process efficiency of WAAM-TIG by in-situ voltage-current-temperature monitoring and feedback control system. *Int J Precis Eng Manuf* 2025, vol. 26, no. 7, pp. 1673–1681. <https://doi.org/10.1007/s12541-024-01208-z>.
 54. Shi C, Du F, Wu Q. A digital twin architecture for wireless networked adaptive active noise control. *IEEE/ACM Trans Audio Speech Lang Process* 2022, vol. 30, pp. 2768–2777. <https://doi.org/10.1109/taslp.2022.3199992>.
 55. Wang S, Wang J. Safety of offshore platforms. In: Cui W, Fu S, Hu Z, editors. *Encyclopedia of ocean engineering*. Springer; 2022. pp. 1519–1527. https://doi.org/10.1007/978-981-10-6946-8_25.
 56. Li Z, Hou Z, Pan Z, Wu D, Xu J. A nonautoregressive dynamic model based welding parameter planning method for varying geometry beads in WAAM. *IEEE Trans Ind Electron* 2022, vol. 70, no. 3, pp. 2770–2779. <https://doi.org/10.1109/tie.2022.3172762>.
 57. Hoffman R, Friedman P, Wetherbee D. Digital twins in shipbuilding and ship operation. In: Crespi N, Drobot AT, Minerva R, editors. *The digital twin*. Springer; 2023. pp. 799–847. https://doi.org/10.1007/978-3-031-21343-4_28.
 58. Li L, Aslam S, Wileman A, Perinpanayagam S. Digital twin in aerospace industry: A gentle introduction. *IEEE Access* 2021, vol. 10, pp. 9543–9562. <https://doi.org/10.1109/access.2021.3136458>.