Supergen ORE Hub Flex Fund Project

Corrosion and fatigue protection of offshore wind Turbine structures using additive manufacturing technology (COATing)

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1- Project Summary

An efficient source of renewable energy, which is increasingly the preferred solution for realising Britain's short- and long-term energy ambitions, is offshore wind. While Britain is presently the global leader in offshore wind energy, the national target set by the UK government to increase the installed capacity of offshore wind energy from approximately 10 GW in 2020 to 40 GW in 2030 demonstrates the strategic importance of this clean source of energy in the UK's energy mix. The rapid expansion of the installed offshore wind capacity will not only maintain and escalate UK's position in this emerging market, but will also significantly contribute to the UK's world-leading net-zero greenhouse gas emissions target by 2050. Offshore wind turbines (OWTs) are typically designed for 20-25 years of operation. One of the main barriers in extending the operational life span beyond 25 years is the evolution of corrosion-fatigue damage due to the constant exertion of wind, wave and current variable amplitude forces in the highly corrosive environments. Although these structures are designed for operation under corrosion-protection condition, the surface coating and cathodic protection have a finite life beyond which the corrosion protection mechanisms need to be repaired and during this process the structures are subjected to corrosion damage in conjunction with the progressive fatigue damage. The overall aim of this project is to introduce a permanent and maintenance-free additively manufactured protective layer, as an effective and novel coating technology, in the critical areas of OWT support structures. This will maximise life, reduce the number of frequent inspections and deliver a direct beneficial impact on Operations and Maintenance (O&M) costs.

The proposed research aims to adopt the advances in additive manufacturing technology to create damage tolerant regions in the critical hot spots of offshore wind turbines, such as circumferential welds in monopiles particularly near the mudline. The importance of the proposed research lies in performing an underpinning feasibility study using advanced manufacturing technologies to enhance the resilience of future generation of offshore wind infrastructure and enable life extension and repowering at the end of initial design life in the existing offshore wind farms. Additive manufacturing is not a competing technology to traditional high volume production techniques such as multi-pass welding in offshore wind monopile foundations, but complimentary to impart engineered strengthening that would increase the overall life and decrease the offshore wind levelised cost of energy (LCoE). The successful completion of this project will lead to a wider research to significantly enhance the durability and damage tolerance of OWT monopiles by employing advanced manufacturing techniques. The results from the proposed feasibility study will open new research avenues to optimise OWT structures dimensions, reduce the fabrication costs through material savings, optimise the inspection frequencies, enhance corrosion protection (i.e. coating) technologies, improve fatigue durability and finally increase the operational life of OWT support structures to 25+ years, hence reducing the LCoE.

2- Background

- An efficient source of renewable energy, which is increasingly the preferred solution for realising Britain's energy demand, is offshore wind.
- Offshore wind turbines (OWTs) are typically designed for 20-25 years of operation.

- One of the main barriers for extending the operational lifespan of OWT support structures is the evolution of corrosion-fatigue damage.
- The surface coating and cathodic protection have a finite life, beyond which they need to be repaired.
- During this process the structures are subjected to free-corrosion condition in conjunction with the progressive fatigue damage.
- There is an essential need to develop long-lasting protective layers, in the critical areas of OWT support structures, in order to extend the lifespan, optimise and reduce the number of frequent inspections and subsequently reduce costs.

3- Aims and Objectives:

This research project aims to adopt the advances in additive manufacturing technologies (e.g. WAAM and LMD) to create damage tolerant regions in the critical hot spots of OWTs, such as circumferential welds in monopiles. This can be achieved through the following project objectives:

- To develop corrosion-fatigue tolerant matrix microstructures using additive manufacturing techniques to inhibit damage evolution at the micro- and meso level;
- To quantitatively analyse the corrosion and fatigue resistance of additively manufactured coupons compared to traditional multi-pass butt-welded geometries;
- To propose optimum multi-metallic alloys combination and the cost-effective additive manufacturing technique for corrosion-fatigue life enhancement in OWT support structures;

4- Fabrication of WAAM Walls

The wire arc additive manufacturing (WAAM) technique has been used in this project to produce four walls using ER70 steel which has relatively low corrosion resistance. In the next part of the project, hybrid WAAM walls were manufactured by simultaneous deposition of ER70 and ER90 wires with the view to enhance the corrosion resistance of the produced component. An example of a WAAM wall produced in this project is shown in Figure 1.

Figure 1: An example of a WAAM wall produced using ER70 steel

5- Microstructural Analysis

The material microstructure in ER70 and hybrid WAAM walls was thoroughly analysed using optical microscopy and scanning electron microscopy (SEM) techniques. The results from microstructural analysis on ER70 walls have been shown in Figure 2 where the material microstructure has been studied at different parts of the wall.

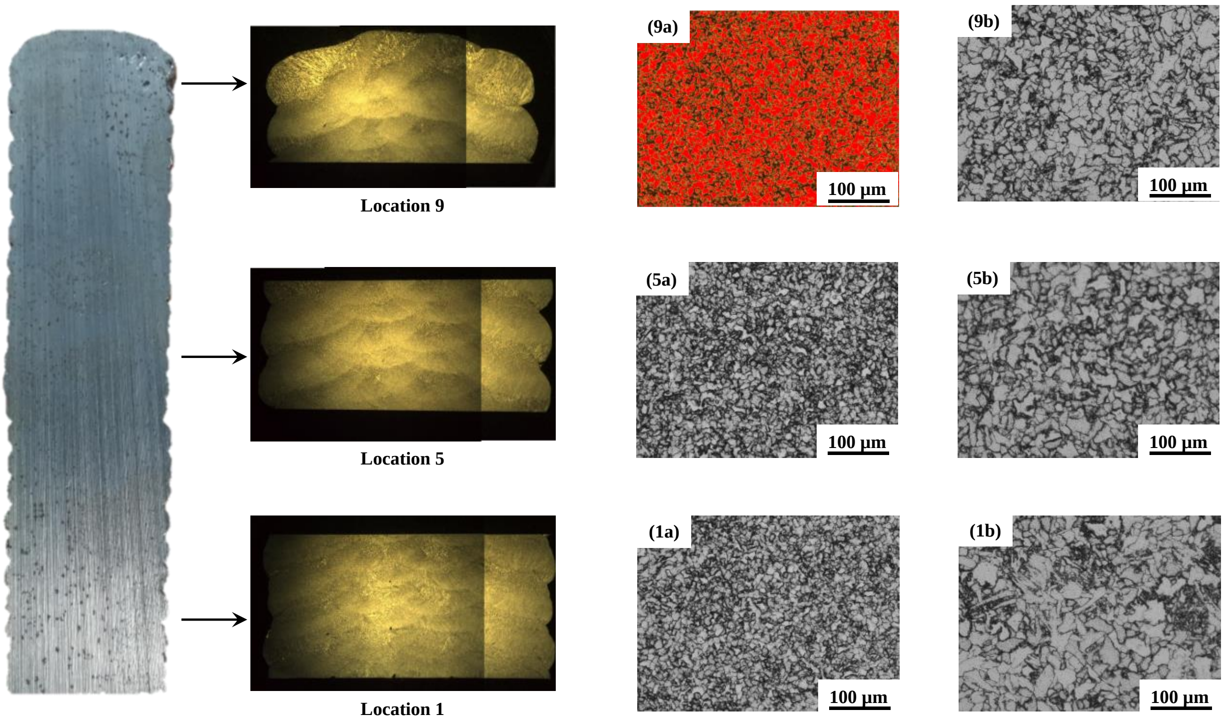

Figure 2: Comparison of material microstructure at different parts of ER70 WAAM walls

6- Hardness Analysis

Hardness analysis was carried out on an off-cuts extracted from ER70 and hybrid WAAM walls. Hardness tests were conducted using two different load levels of 0.3kg and 10kg and the results are presented in Figure 3. The results show an increase in the local hardness value in the deposited layers located at the top of the wall compared to the bottom layers.

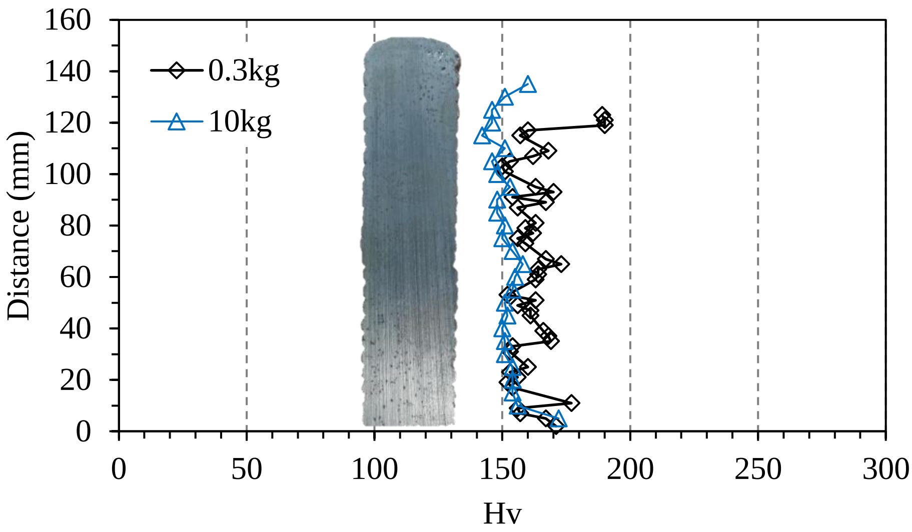

Figure 3: Hardness test results on ER70 WAAM walls

7- Specimen Extraction

Four types of specimens have been extracted from each of the ER70 and hybrid (i.e. ER70+ER90) WAAM walls, including (a) tensile test specimens, (b) S-N uniaxial fatigue test specimens, (c) Fracture toughness tests specimens, and (d) fatigue crack growth (FCG) test specimens. All samples were extracted from the WAAM walls using the Electrical Discharge Machining (EDM) technique to minimise the cutting effects on the subsequent test results. All test specimens were designed according to international standards with the dimensions specified in relevant ASTM standards for each test geometry. The designed specimen geometries and key dimensions for each test type are demonstrated in Figure 4.

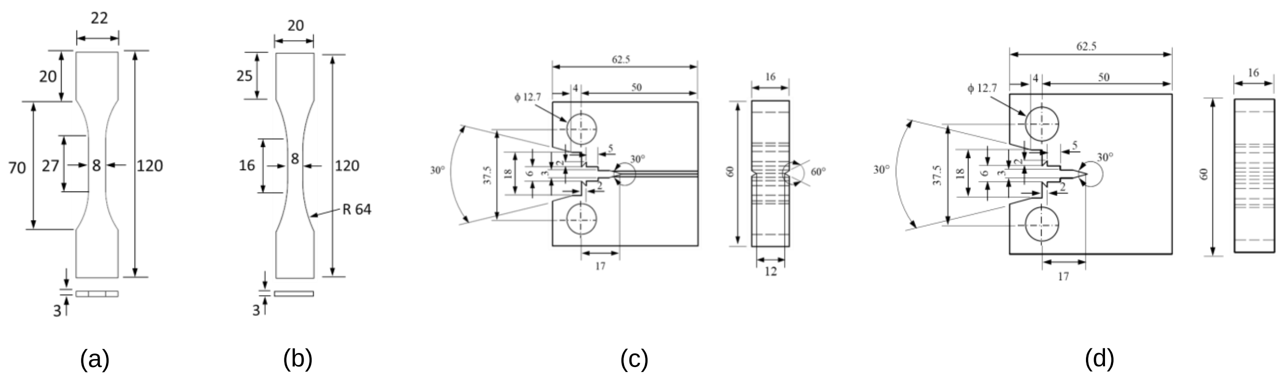

Figure 4: Specimen geometries for (a) tensile test, (b) S-N uniaxial fatigue test, (c) fracture toughness test, (d) FCG tests

8- Exposure to seawater

In order to introduce corrosion damage into the test specimens, artificial non-biological seawater was prepared according to ASTM D1141. The uniaxial fatigue samples were immersed in artificial seawater for different exposure times. Prior to immersion in seawater, the gripping ends of dog bone samples were covered with a thick layer of silicon protection to avoid corrosion damage being introduced in the gripping section. The samples were then immersed for zero and two months in artificial seawater as shown in Figure 5 .

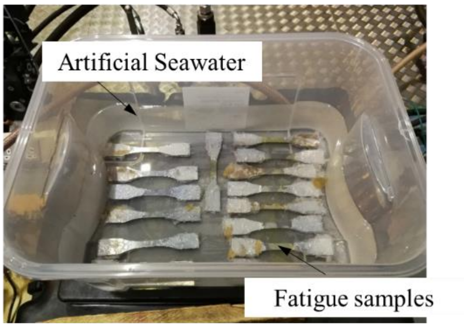

Figure 5: Exposure of fatigue samples to seawater

9- Fatigue testing

The fatigue samples were initially immersed in artificial seawater for different durations of 0 and 2 months and subsequently tested in air at different stress levels with the load ratio of 0.1 and frequency of 20 Hz. The results from fatigue tests are presented in Figure 6. The indicative S-N curves in Figure 6 show that hybrid (ER70+ER90) samples exhibit enhanced fatigue life both in air and free-corrosion condition, compared to ER70. This proves the suitability of the research hypothesis that hybrid additive manufacturing can be used as an effective technique to enhance the corrosion-fatigue behaviour in the critical regions of offshore wind turbine foundations.

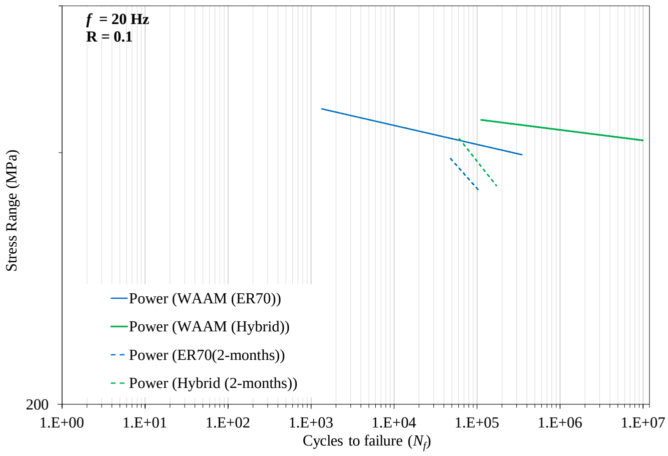

Figure 6: Comparison of the S-N curves