SSC Project Recommendation for FY 2021

In Situ Digital Repair of Sensitized Aluminum Structures in Marine Environments

1.0 OBJECTIVE.

1.1 The objective of this project is to develop a new digital repair framework for aluminum ship structures damaged by sensitization. Bespoke parts will be manufactured *in situ* to restore the original functionality of the structures. The repair process and effectiveness will be demonstrated through a feasibility study using both experimental methods and advanced data analytics.

2.0 BACKGROUND.

2.1 5xxx series aluminium alloys have been used extensively in the US Navy ships due to their good balance of weight and as-welded strength. The applications ranges from primary structures, deck plates to superstructures and ducts [8.1]. These alloys are considered to have good general resistance against marine corrosion at ambient temperatures. However, it has been reported that the temperature of decking exposed to direct sunlight in hot climate can reach in excess of 70 °C [8.1]. In such conditions, alloys with more than 3% Mg content can become sensitized, leading to integranular corrosion (IGC) and integranular stress corrosion cracking (IGSCC).

2.2 It is well-established that the IGC of 5xxx alloys is attributed to the presence of the β-phase (Al_3Mg_2) along grain boundaries or at incoherent interfaces such as intragranular particles (such as Al_6Mn) or dislocations. The β-phase precipitation can be significant at temperatures from ~50 to 220°C [8.2]. This results in the formation of micro-galvanic cells with the β-phase being more anodic and the Al α-phase being more cathodic. When the degree of sensitization (DoS), defined as per ASTM B928 through the ASTM G67 test, exceeds 25 mg/cm^2, the material is considered sensitized. Corrosion occurs with β-phase dissolution, grain fallout and stress corrosion cracking when there are sufficient tensile stresses.

2.3 A survey between 1990 and 2015 shows that the majority of the 6000+ cracks found in ship inspections has been documented as IGSCC [8.1]. This is particularly pertinent on plates with H116 temper. To alleviate this issue, a range of restoration and repair methods have been implemented. Grain boundary engineering and reversion heat treatment have been utilized to rectify the sensitized microstructure [8.2]. When damage or cracks are present, common repair methods include manual welding repair, insert repair, ultrasonic peening, composite patch and bonded aluminum sheet [8.1]. However, there are limitations associated with these methods, such as high heat input, microcracking or micro-tearing, load-bearing constraints and short duration. Additionally, the ultrasonic peening is only suitable for the intermediate DoS range between 30 to 60 mg/cm^2 [8.1].

2.4 With the rapid advancement in manufacturing technologies, it is foreseen that the manual/traditional repair processes can be replaced by digital restoration. The movement toward automated repair and restoration requires a reliable and efficient method to guarantee that the damaged part is brought back to its original condition ready to enter the next life cycle. Additive manufacturing (AM) is the primary solution for this. The traditional use of AM technologies is mainly focused on printing new parts, which either provide a key function on their own, e.g., AM propellers, or integrate into a system, e.g., AM suspension arms. However, this technology can also be utilized to restore damaged structures to as-new conditions.

2.5 Currently, the greatest utilization of digital repair is within the aircraft industry, where components such as turbine blades are repaired based on a geometric reconstruction algorithm [8.3]. Additive processes have also been utilized within the marine industry; however, this has been limited to repairing marine engine crankshafts [8.4, 8.5]. Overall, across all industries, the majority of repairs are conducted on metallic parts, such as Ti6Al4V, Inconel 625/718, Cr-Ni alloys and stainless steels. Direct energy deposition (DED) is the most commonly used method, specifically the laser cladding and laser metal deposition, which allows layer-by-layer restoration of damaged components. Other techniques include: cold spray AM and the powder bed fusion (PBF) technique (electron beam melting) for reconstructions of gas turbine burners. However, PBF takes place within a limited machine volume and requires post-treatment trimming of surfaces before the component can enter service, which restricts its application for *in situ* repair.

2.6 The repair process often involves reconstructing the damaged component surface with reverse engineering of the original geometry. While PBF is capable of fabricating components of almost any shape, DED is relatively constrained when printing complex geometries. Therefore, pre-processing is key. This includes scanning and deriving the intersection between the as-designed and damaged model. The prominent cross section method with surface extrapolation may be used when the as-designed model is not available. However, systematic studies on the interface properties, engineering tolerance, material compatibility and the restored component performance are limited.

2.7 This project proposes a digital repair method using a low energy input arc AM technique, aiming to fully restore the corrosion resistance and mechanical properties of a sensitized/damaged AA5456-H116 structural component to its as-new condition. The process will be demonstrated using a mock structure subject to sensitization and IGC. The quality of the repair will be assessed by comparing with the as-built structure and conventional welding repair. The process data will be collected and fed into a deep learning neural network to quantify their influences on the resultant microstructure and structural performances.

3.0 REQUIREMENTS.

3.1 Scope.

3.1.1 The Contractor shall conduct an assessment of the sensitization problem on light-scantling aluminum ships. This will be achieved through a literature review with emphasis on the operational environments (chemical and mechanical) and the performances/quality of existing repair methods for IGC and IGSCC. A key structural component shall be identified as the focus of the feasibility study.

3.1.2 The Contractor shall preproduce a mock structural component using AA5456-H116 subject to IGC. Both the new digital repair and traditional weld repair shall be conducted. All process data shall be recorded.

3.1.3 The Contractor shall assess the quality of the new repair by characterizing the microstructures, the DoS and mechanical properties, for which a database will be generated. Attention should be paid on whether these are fully restored to as-design or as-new equivalent.

3.1.4 The Contractor shall use the collected data and the newly developed artificial neural networks (by the Contractor) to quantify the relationship between the original damaged status, the AM processes and the final repair quality. Such information will be valuable to determine the optimum repair point and the AM settings for future repairs.

3.2 Tasks. (Identify the tasks to carry out the scope of the project).

3.2.1 The Contractor shall conduct a comprehensive literature review to fully understand the problem.

3.2.2 The Contractor shall reproduce two identical representative aluminum structural parts, e.g., T-joints (typical dimensions of a few hundred millimeters), using AA5456-H116 and characterize the as-built properties.

3.2.3 The Contractor shall develop a testing strategy to induce sensitization/IGC on the aluminum parts and quantify the extent of damage at micro- and macrostructural levels.

3.2.4 The Contractor shall perform manual weld repair on an identical aluminum part with damage at the same location and of the same extent.

3.2.5 The Contractor shall develop a digital repair strategy to restore the damaged part to its as-build/as-new condition. This includes determining the reverse engineering process, any required clamping or tooling requirements and a range of AM process parameters.

3.2.6 The Contractor shall establish appropriate metrics to evaluate and compare the quality of the two repair methods. These include metallurgical analysis and basic mechanical testing.

3.2.7 The Contractor shall further develop the artificial neural networks to allow mapping between input variables (chemical compositions, thermal history and repair processes) with the output repair quality based on 3.2.6. Mechanistic understanding and a new database of the repaired material performances will be gained through the above tasks.

3.3 Project Timeline.

The project will start once the contract is awarded and will follow the time plan below:

Scope 3.1.1:
- Task 3.2.1: Months 1-2

Scope 3.1.2:
- Task 3.2.2: Months 2-3
- Task 3.2.3: Months 3-4
- Tasks 3.2.4 and 3.2.5: Months 5-7

Scope 3.1.3:
- Task 3.2.6: Months 7-10

Scope 3.1.4:
- Task 3.2.7: Months 1-2 and 9-11

Progress report: Months 3, 6, 9, 11-12.

4.0 GOVERNMENT FURNISHED INFORMATION.

4.1 Standards for the Preparation and Publication of SSC Technical Reports.

5.0 DELIVERY REQUIREMENTS.

5.1 The Contractor shall provide quarterly progress reports to the Project Technical Committee, the Ship Structure Committee Executive Director, and the Contract Specialist.

5.2 The Contractor shall provide all raw data and analysis generated in the project.

5.3 The Contractor shall provide a print ready master final report and an electronic copy, including the above deliverables, formatted as per the SSC Report Style Manual.

6.0 PERIOD OF PERFORMANCE.

6.1 Project Initiation Date: date of award.

6.2 Project Completion Date: 12 months from the date of award.

7.0 GOVERNMENT ESTIMATE. These contractor direct costs are based on previous project participation expenses.

7.1 Project Duration: 12 months.

7.2 Total Estimate: $100,000.

8.0 REFERENCES.

8.1 Golumbfskie, W.J., Tran, K.T., Noland, J.M., Park, R., Stiles, D.J., Grogan, G. & Wong C. (2015) Survey of detection, mitigation and repair technologies to address problems caused by sensitization of Al-Mg alloys on navy ships. *CORROSION*, 72, pp.314-328.

8.2 Zhang, R., Knight, S.P, Holtz, R.L., Goswami, R., Davies, C.H.J. & Birbilis, N. (2016) A survey of sensitisation in 5xxx series aluminium alloys. *CORROSION*, 72, pp.1455-159.

8.3 Rahito, D.A.W. & Azman, A.H. (2019) Additive manufacturing for repair and restoration in remanufacturing: An overview from object design and system perspectives. *Processes*, 7, 802.

8.4 Koehler, H., Partes, K., Seefeld, T. & Vollertsen, F. (2011) Influence of laser reconditioning on fatigue properties of crankshafts. *Physics Procedia*, 12, pp.512-518.

8.5 Torims, T., Pikurs, G., Ratkus, A., Logins, A., Vilcans, J. & Sklariks, S. (2015) Development of technological equipment to laboratory test in-situ laser cladding for marine engine crankshaft renovation. *Procedia Engineering*, 100, pp.559-568.

9.0 SUGGESTED CONTRACTING STRATEGY.

9.1 It is suggested that the project will be led by a research team at the University of Southampton, collaborating with the Arc Processes and Welding Engineering Section at TWI Ltd. Within the University of Southampton, the Maritime Engineering Group and the National Centre for Advanced Tribology at Southampton are world-leading groups in both fundamental and applied research on marine degradation/corrosion and the life-cycle analysis of ship structures. This includes the access of the Iridis High Performance Computing Cluster and the state-of-the-art testing/analysis facilities. The environmental chambers, electrochemical test set, optical and scanning/transmission electron microscopes and micro-CT are well suited to characterize sensitization in great detail.

9.2 TWI Ltd. is at the forefront of materials and joint performance analysis and has a well-established multi-disciplinary team working on innovative manufacturing techniques. They are active in processing, modelling, non-destructive and destructive evaluation of complex AM components using a range of low energy input processes for aluminum alloys.