CORE RESEARCH PROGRAMME

Annual Symposium

7 December 2023

TWI-GLOBAL.COM/CRP

WELCOME

CORE RESEARCH PROGRAMME ANNUAL SYMPOSIUM

A warm welcome to our second, annual TWI Core Research Programme (CRP) Symposium here at TWI Cambridge, UK! Building on the achievements of last year's event, we have an exciting programme planned for today.

TWI's flagship, applied research and development programme is designed to meet the needs of our Industrial Member companies. Projects are selected to address the most pressing technological and industrial challenges being faced by TWI and its Industrial Members, and span the broader subject areas of engineering, manufacturing and materials. In addition, the CRP also supports engineers of the future by funding several National Structural Integrity Research Centre (NSIRC) PhD students each year.

Detailed CRP research and project material, including the newly introduced CRP technical webinars, are available solely to TWI Industrial Member companies as a key component of their membership. However, to demonstrate the positive impact the CRP has on wider industry, summary and headline information is also made freely available online to the international engineering community.

The aim of the Symposium is for you, as a TWI Industrial Member, to take a deep dive into the technological and industrial aspects of the CRP, including projects being worked on by NSIRC PhD students. CRP projects are aligned with TRLs 4-6 and are currently focused on the key areas of digitalisation, data and digital twin, net zero, new materials and circular economy, and smart manufacturing. During the day there will be a series of technology sessions with discussion panels, informative presentations, a Technology Forum for 1-2-1s with TWI research leads, a technical poster display, and time to network with fellow Industrial Members and TWI staff.

I would like to thank the TWI CRP Directors Dr Paul Woollin, Research Director, and Prof Tat-Hean Gan, Membership, Innovation and Global Operations Director, the CRP Research Board and Technical Committee Members, and TWI's technical staff for their contribution and dedication to the programme, and its ongoing success.

Finally, I hope you enjoy the CRP Symposium 2023, and would ask you to join me in thanking TWI's Research and Innovation Operations (RIO) team who have organised today's event.

Visit the CRP Website for an in-depth look at this flagship TWI programme.

Simon Webster
Chair, Research Board
TWI CRP

TWI CRP AND WIDER CONTEXT

CORE RESEARCH PROGRAMME ANNUAL SYMPOSIUM

Prof Tat-Hean
Core Research Programme Director, and Membership, Innovation and Global Operations Director, TWI

As another successful TWI Core Research Programme (CRP) year draws to a close, I am delighted to welcome you to TWI Cambridge again for this second, annual TWI CRP Symposium.

2023 has been a research-rich year for the CRP, with an assortment of technologically and industrially relevant projects either instigated, achieving significant milestones or completed. All of these have an overriding objective of delivering real-world operational benefits to you, our Industrial Members, in today's fast moving and dynamic environment. New projects kicked off in 2023 are focused on some of the most pressing issues for Industrial Members, both now and in the future, in the context of digitalisation, data and digital twin, net zero, hydrogen and low carbon technologies, and smart manufacturing. Specific projects being undertaken range from developing a digital twin demonstrator for real-time integrity assessment of crack growth, through to internal bore coatings for use in corrosion and hydrogen environments, and enabling automated quality control of the wire arc directed energy deposition build process.

In June this year, we launched the new CRP Rapid Proposal Call (RPC) to fund projects of a 6-month duration, with Project Leaders being invited to submit their technology concepts supported by a 'Dragon's Den' style presentation. These short-term projects go through an accelerated review process and are designed to deliver quick results that could then contribute to future, full-scale, CRP projects or underpin other research projects across TWI.

This year, we also continued to expand on the promotion and dissemination of the CRP, most notably, with the introduction of quarterly CRP webinars, four of which have now been delivered, and the creation of a dedicated CRP Media and Events section on the CRP website, drawing together for the first time, all the CRP press releases, insights, events and videos into one, easy-to-access area. These initiatives serve to extend the reach of the programme, increase its visibility and further demonstrate its impact.

While the flagship CRP is central to ensuring our services remain relevant to Industrial Members, it also sits within the wider context of a much larger, holistic offering from TWI that brings together the synergies of different programmes, Membership types and activities so that Industrial Members can benefit as fully as possible from what is available.

TWI's Collaborative Projects Programme enables Industrial Member companies to engage in collaborative research and development (R&D) proposals that are accurately targeted at attracting competitively won grant funding from UK and EU research programmes. This is facilitated by TWI's Technology Innovation Management team which works with TWI's Innovation Centres and Technical Sections to develop novel technology concepts aligned to specific grant (public) funding competitions (calls), forms project consortia matching Industrial Members with like-minded SMEs and the most technologically relevant Innovation Centres and TWI Sections, and supports consortium partners through the ensuing stages of proposal writing, budgeting and quality checks, through to submission of the final bid document. Industrial Members who are not yet involved in this type of project can explore upcoming opportunities by attending one of our regular UK & EU Collaborative Opportunities and Brokerage webinars, for which new dates will be announced in 2024.

In other areas, a key initiative of this year, and set to continue for 2024, has been the delivery of high profile, TWI technical and industry events in regions around the world. Examples include the Energy Transition – Structural Integrity Challenges Conference, held in Scotland, the TWI China Conference 2023: Advanced Manufacturing Technologies and Structural Integrity, co-hosted with the Jiangsu Industrial Technology Research Institute (JITRI) in China, and the TWI Energy and Construction Industry Panel Meeting: Driving to a

TECHNOLOGY HIGHLIGHTS

CORE RESEARCH PROGRAMME ANNUAL SYMPOSIUM

Net Carbon Future for the Energy and Construction Industries, in the United Arab Emirates. These occasions bring Industrial Members together with companies and organisations from across the supply chain to debate, share and innovate towards the development of viable, cost effective solutions for global industry.

The Welding Institute also marked a major achievement in 2023, celebrating its 100th anniversary, during which we reinforced our commitment to creating a deeper, more value-driven relationship between our Professional (of The Institute) and Industrial Members internationally. The aim is to enable Members in different regions to benefit from the cross fertilisation of skills, best practice, experience and knowledge exchange, and improve the potential for Member-to-Member networking, thereby contributing to both the Professional Member's career growth, and the Industrial Member company's ability to innovate and safeguard its competitive position.

Next year will see a continuation of our strategy to elevate the level of TWI's engagement with Industrial Members, so that you and your company derive the best possible value and benefit from your Membership. This includes supporting Industrial Members with innovation through the development of new, market-aligned products, services and capabilities that can provide an advantage in emerging and fast growing sectors, providing enhanced localised assistance in different geographic regions, increasing the number of global panel meetings, expanding the new TWI Digital Library further and more.

Lastly, I hope you enjoy the CRP Symposium 2023 and I look forward to speaking to many of you during the course of the day.

Dr Paul Woollin
Core Research Programme Director, and Research Director, TWI

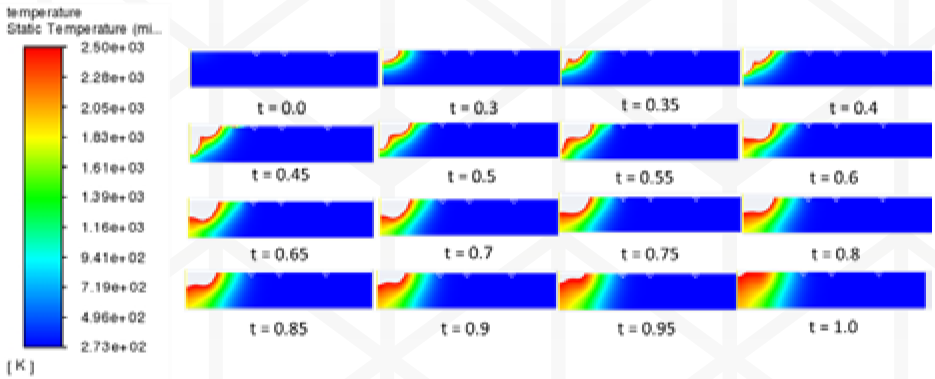
The TWI Core Research Programme (CRP) contributes to the delivery of TWI's Technology Roadmap and develops new data, knowledge and laboratory capabilities to support Industrial Members, as they strive to gain competitive advantage by safely and securely adopting new technology to balance long term sustainability and short term profitability. It also provides learning and technology watch opportunities for TWI engineers and the Research Committees.

With 65 live projects in the current CRP portfolio, 19 of which are also supporting NSIRC PhDs, the programme continues to provide a rich seam of technological developments and reflects the £3m+ of funding that has been released for the programme in 2023. This year there are also six, Rapid Proposal Call (RPC) projects to add to the total, each of which has a 6-month duration and may go on to demonstrate principles that form the basis of a future CRP project.

The following are just three examples of CRP projects that have reported in 2023 and created new capabilities with potential to generate impact for Industrial Members, in support of their innovation programmes and commercial activities.

Robotic arc welding and additive manufacturing

Multi-axis industrial robots are widely implemented in arc welding production and additive manufacturing (AM) due to their ability to increase productivity and improve quality. As a result, robotic arc processes are faced with accommodating increasingly more complicated applications and materials. Therefore, the aim of



Contour plot of static temperature (K) at different times (s) during the welding process – travel speed: 500mm/min this project was to optimise process parameters through utilisation of a state-of-the-art numerical modelling approach and a real time weld monitoring system linked to an industrial welding robot.

The concept of utilising numerical modelling to enable automatic parameter development and refinement for robotic arc welding was found to be feasible. Furthermore, the finite element (FE) and computation fluid dynamics (CFD) based numerical modelling, calibrated using the data collected from representative welding and monitoring trials, showed effective prediction of the impact of welding parameters on the formation of the weld, and were more representative than the conventional modelling approach. This now provides a platform to support future industrial needs related to simplifying and automating parameter development for robotic arc welding and AM.

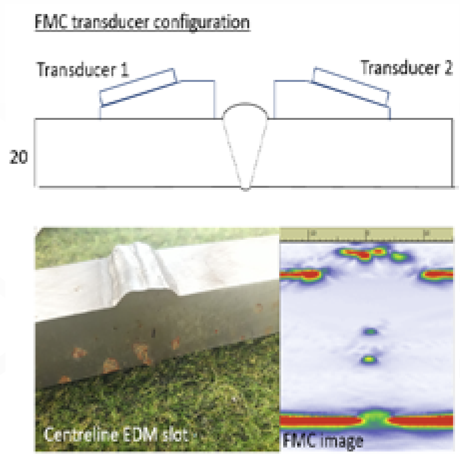
Industry guidelines on the fatigue performance of large bolts

Threaded fasteners are used in a range of industries for a wide variety of reasons, but failures persist, particularly in large bolts, and many applications cause the fasteners to experience cyclic loads. Existing fatigue design guidance exists for standard sized bolts, but when threaded fasteners need to withstand higher, applied forces, much larger sizes are needed, such as the M72 bolts used in the internal ring flanges in wind turbine substructures. With no fatigue design guidance for large bolts currently available, the objective of this project was to provide a summary of key considerations when using large bolts in fatigue service.

Failure particularly occurs where bolted joints are complex, with critical factors including material selection, quality control, joint design, fatigue performance, and the methods used to apply and monitor preload. To enable prediction of the fatigue performance of a bolt within a joint, the primary parameter is the stress range experienced by the bolt. In the internal flange connections in wind turbine towers, relationships exist which link tower load with bolt load, but these can under-predict bolt load. The most accurate way to characterise the load that a bolt is experiencing is to measure it using strain gauges or direct tension indicators. The project report summarises recent research and relates this to standards and existing guidance, thus providing comprehensive industry advice.

Feasibility of FMC pitch-catch for inspection of pipeline girth

This project investigated the feasibility of using an ultrasonic array, full matrix capture (FMC) pitch-catch setup to reliably and accurately locate, detect and size planar through-wall flaws in pipeline girth weld components, as a potential replacement for one of the most widely used current industry standard techniques, namely conventional time-of-flight diffraction (ToFD) channels. The rationale was that a successful FMC pitch-catch arrangement would potentially offer significant cost savings through reduced operator training and setup, increased reliability of inspection, and the potential to perform FMC pulse-echo and pitch-catch scans simultaneously using a single pair of ultrasonic array transducers.



FMC girth weld setup, showing a 20mm thick plate weld containing a centreline electrical discharge machined (EDM) notch

The development of FMC pitch-catch calibration routines, for system latency and probe separation distance, are key steps to ensuring reliable, accurate, through-wall detection and sizing of all flaws. Inspection of a girth weld pipe sample using the FMC pitch-catch technique, combined with pulse-echo and self-tandem inspection modes, achieved an average, through-wall sizing accuracy of 0.3mm for lack of fusion flaws. Moreover, all flaw indications identified with FMC were confirmed in the sectioning data. The FMC pitch-catch mode was shown to outperform the other available inspection modes in terms of through-wall sizing accuracy by an average of 0.1mm, although all modes were required to ensure detection and sizing of all flaws. The FMC pitch-catch inspection mode is now included within BS ISO 23865:2021 and is considered ready for use by industry.

SYMPOSIUM AGENDA

7 December 2023 at TWI Ltd, Cambridge, UK.

08:30	Arrival and Refreshments
09:00	Welcome *Prof Tat-Hean Gan, Core Research Programme Director, and Membership, Innovation and Global Operations Director, TWI*
09:05	Introductory Address *Simon Webster, Chair, TWI Research Board*
09:20	Keynote Speaker *Value and Impact of the Core Research Programme: A Rolls-Royce Perspective* *Richard March, Global Process Lead for Welding and Joining, Rolls-Royce PLC*
09:50	Advancing and Developing New Technologies: TWI's Capability Development Programme *Dr Jon Blackburn, Group Manager - Strategic Programmes for Growth, TWI*
10:05	Move to Break Out Rooms

	LECTURE ROOM ONE	LECTURE ROOM TWO
	Research Stream: Digitalisation & Data	Research Stream: Net Zero
	Session Chairs: Dr Dan Clark and Dr Muhammad Ali, TWI Research Board & TWI Staff	*Session Chairs: Nick Clark and Dr Tanya Sabin, TWI Research Board*
10:10	Presentations from:	Presentations from:
	Artificial Intelligence for NDT Scanning of Unknown Geometries using Collaborative Robots (34241) *Project Manager: Calum Hoyle*	Assessment of the Durability of Abhesive Surfaces (33552) *Project Manager: Dr Tamoor Masood* *Presenter: Dr Ana Antelava*
	Development of Digital Twin Technology as a Demonstrator for Real-Time Integrity Assessment of Crack Growth in Tensile Specimens (35239) *Project Manager Stephen Grigg*	Development of Leak-Before-Break Hydrogen Storage Composite Pressure Vessels (34742) Project Manager: *Hasan Caglar*
	CAM DED – A Review of Directed Energy Deposition CAM Tools to Help Industrial Decision Making (35254) *Project Manager: Dr Jhonattan Gutjahr* *Presenter: Carl Hauser*	Thermoplastic Materials Compatibility for Hydrogen Service (34250) *Project Manager: Dr Ana Antelava*
10:25	**Panel Discussion** *Facilitator: Channa Nageswaren, Consultant*	**Panel Discussion** *Facilitator: Bernadette Craster, Technology Fellow*
10:50	Break for Refreshments	
	Research Stream: Digitalisation & Data	Research Stream: Smart Manufacturing
	Session Chairs: William Wistance and Dr Andrew Den Bakker, TWI Research Board	*Session Chairs: Dr James Murray and Simon Webster, TWI Research Board*
11:10	Presentations from:	Presentations from:
	Development of Coded Excitation Techniques for Non-Metallic Pipes Inspection (34765) *Project Manager: Dr Owen Rees-Lloyd* *Presenter: Calum Hoyle*	Optimising Arc-Based Additive Manufacture using Fracture Mechanics Approaches (34788) *Project Manager: Dr Lei Xu*
	Techniques for High Temperature Ultrasonic Inspection of Arc Welding (34727) *Project Manager: Dr Kai Yang*	AMorph - 4D Printing for Field Morphing Structures (34745) *Project Manager: Dr Ilias Zournatzis* *Presenter: Dr Christos Kazasis*
	In-Process Detection and Non-Destructive Testing of Electron Beam Weld Imperfections (35258) *Project Manager: Dr Channa Nageswaran*	ReMove - Effortless Support Structure Removal for Metal 3D Printing (35476) *Project Manager: Antonis Dimopoulos*

Time	Lecture Room One	Lecture Room Two
		Automated Quality Control of Wire Arc Directed Energy Deposition Build for Smart Manufacturing (35253) *Project Manager: Capucine Carpentier*
11:30	**Panel Discussion** *Facilitator: Ian Cooper, Technology Fellow*	**Panel Discussion** *Facilitator: Shiladitya Paul, Research & Product Development Programme Manager*

11:55 Technology Forum - Exhibition - Networking - Lunch

13:30 Keynote Speaker
Core Research Programme - Solutions for Thales' Underwater Systems Business
Dr Tanya Sabin, Senior Materials Engineer, Thales UK

Time	LECTURE ROOM ONE	LECTURE ROOM TWO
	Research Stream: Digitalisation & Data	Research Stream: Smart Manufacturing
	Session Chairs: William Wistance and Dr Andrew Den Bakker, TWI Research Board	*Session Chairs: Dr James Murray and Simon Webster, TWI Research Board*
14:00	Presentations from:	Presentations from:
	Integrating Probabilistic Approach into British Defect Assessment Procedure (35241) *Project Manager: Dr Yin Jin Janin*	Joining of Additively Manufactured Materials (34730) *Project Manager: Kandarp Amin*
	Fracture Toughness in Aggressive Environments: Effect of Crack Monitoring Techniques on Test Results (34847) *Project Manager: Dr Fokion Oikonomidis*	Coaxial Wire Additive Manufacturing Processes and In-Line Monitoring Tools (34793) *Project Manager: Dr Tom Pinto*
	Development of Structural Health Monitoring Technology for Pressure Containing Pipelines using Guided Waves and Acoustic Emission (35268) *Project Manager: Dandan Liu*	Automation of Composite and Hybrid Joining Process (34718) *Project Manager: Neelmanee Sarin*
		Internal Bore Coatings for Applications in Corrosion and Hydrogen Environments (35283) Project Manager: Dr Kylee Yingwei Wu *Presenter: Carl Hauser*
14:20	**Panel Discussion** *Facilitator: Charles Schneider, Technology Fellow*	**Panel Discussion** *Facilitator: Alan Taylor, Technology Fellow*

14:45 Break for Refreshments

Time	Lecture Room One	Lecture Room Two
	Research Stream: New Materials & Circular Economy	Research Stream: Net Zero
	Session Chairs: Nick Clark and Dr Tanya Sabin, TWI Research Board	*Session Chairs: Dr James Murray and Dr Muhammad Ali, TWI Research Board & TWI Staff*
15:10	Presentations from:	Presentations from:
	REACH Compliant Aluminium Pre-Treatments (33541) *Project Manager: Dr Kranthi Maniam*	Development of Friction Stir Welding for Hydrogen Fuel Storage Tanks (34741) *Project Manager: Dr Pedro De Sousa Santos*
	Establishing Assessment Methods for Determining Safe Service Limits of High-Temperature Materials in Extreme Environments (34729) *Project Manager: Dr Dorothy Winful*	Hydrogen Embrittlement Reduced by Oxygen and Moisture (HEROM) (35410) *Project Manager: Kasra Sotoudeh*
	Long Term Behaviour of Polymeric Liner Materials/ Coatings in Hydrogen Service (35255) *Project Manager: Dr Ana Antelava*	Enhanced Understanding of Degradation Environments that Develop at Metal/Non-Metal Interfaces for Carbon Capture, Utilisation and Storage Environments (35264) *Project Manager: Dr Amir Shamsa*
15:35	Panel Discussion *Facilitator: Melissa Riley, Consultant*	Panel Discussion *Facilitator: Kasra Sotoudeh, Materials Integrity and Performance Section Manager*

15:55 Move to Lecture Room One

16:00 Awards and Closing Words
Simon Webster, Chair, TWI Research Board

16:15 End

KEYNOTE SPEAKERS

CORE RESEARCH PROGRAMME ANNUAL SYMPOSIUM

Richard March
Global Process Lead for Welding and Joining, Rolls-Royce

Room 1, 09:20

As the Global Process Lead for Welding and Joining at Rolls-Royce, Richard holds responsibilities in the aerospace, nuclear and energy sectors. In addition, he is leading a programme to reduce the occurrence of manufacturing defects across Rolls-Royce's supply chain.

Richard is a Chartered Engineer with the Royal Aeronautical Society and a Fellow of The Welding Institute.

Dr Tanya Sabin
Senior Materials Engineer, Thales UK

Room 1, 13:30

Following a degree in Materials Science and Metallurgy, and a PhD in metallurgy, Tanya moved into industry as a Materials and Processes Engineer and has worked in aerospace, space and defence companies. She has been involved in various projects and interactions with TWI over the years, including day-today support on conventional welding and NDT and, increasingly, on research and development in additive manufacturing particularly.

Four years ago, Tanya joined Thales' underwater systems business and saw quite a different set of materials and environments from previous jobs.

Through her role within TWI's Technical Committee, Tanya has noticed many common challenges with industries such as nuclear and wind energy, and is passionate about finding ways we can work together to all benefit from new technologies.

TWI SPEAKER

Dr Jon Blackburn
Group Manager, Strategic Programmes for Growth, TWI
TWI Ltd

Room 1, 09:50

Jon joined TWI in 2006, initially working within the Advanced Manufacturing Group and subsequently leading the Materials and Structural Integrity Group.

Jon is currently responsible for establishing and delivering TWI's Capability Development Programme, which represents a portfolio of circa £10m of activity, ensuring that TWI is well positioned to support the future needs of its Industrial Members. Additionally, he has led the development of TWI's 5-year Technology Roadmap and championed TWI's strategic response to the hydrogen economy.

Jon has a Masters Degree in Mechanical Engineering and a Doctorate in Advanced Manufacturing. Outside of TWI, Jon has previously served as President and Non-Executive Director for the UK's Association of Industrial Laser Users.

Simon Webster
Chair, Research Board

Simon is retired after a 34-year career with BP. He held technical and leadership roles in Aberdeen, Moscow and London, and more recently was VP for Technology and BP's first Chief Engineer for corrosion, inspection and materials.

Currently he has a retirement portfolio, including volunteering for a local gardening charity supporting elderly and vulnerable people. He also undertakes selected engineering consultancy, and is a Non-Executive Director of TWI and chairs their Research Board. Most importantly, he enjoys spending time with family and friends, and on his passion of hiking.

Daniel Clark
Vice-Chair, Research Board
TWI Council Member

William Wistance
Principal Specialist Supply Chain Assurance Services, Lloyd's Register EMEA

William's role focuses on the quality assurance of materials, equipment and components certified for the use in the marine and offshore sectors, as well as classification and certification of marine assets ensuring that they can operate to the highest levels of safety and environmental compliance.

He is also the Chair of the TWI Engineering Technical Committee.

William is a Chartered Engineer with over 24 years' experience in the marine and offshore sector, and has a degree in Materials Science and Engineering.

His career has been focused on metallurgy and materials including research, manufacturer assessments, production quality and the assessment of new technologies.

Nick Clark
Technical Manager, Materials and Processes, Baker Hughes

Nick graduated in Materials Engineering from Swansea University in 1992 and worked in the aviation industry for Fairey Hydraulics supporting all aspects of materials engineering but specialising in special process development.

In 2008 he moved into the oil and gas industry working for Baker Hughes (then GE Oil & Gas), initially as Materials Engineering Manager for subsea controls before moving into global materials engineering manager role for subsea production systems, until taking up his most recent role as Technical Manager for materials and processes for subsea production systems.

NIck's role holds responsibility for materials selection, welding and corrosion control across multiple product lines including subsea x-mas trees and other subsea structures. He is a member of the Institute of Materials and an associate member of The Welding Institute.

Gary joined Rolls-Royce in 2006 and focused his career on innovation and technology roles.

In 2012, Gary moved into a Programme Management position with accountability for Manufacturing Technology Capability and specific responsibility for external projects conducted via the Rolls-Royce Advanced Manufacturing Research Centre (AxRC) network. These technology projects deliver TRL maturity and include multiple technology areas.

In 2019, Gary moved to a role as Manufacturing Innovation Manager, leading a multi-million pound technology programme looking to bring innovative processes into nuclear manufacturing.

In 2021, Gary became the Head of Manufacturing Innovation and is leading innovation and technology programmes to advance the capability of manufacturing to support new and novel Rolls-Royce power products in exciting new domains, such as space.

Gary Jones
Head of Manufacturing Innovation, Rolls-Royce

Following a degree in Materials Science and Metallurgy, and a PhD in metallurgy, Tanya moved into industry as a Materials and Processes Engineer and has worked in aerospace, space and defence companies. She has been involved in various projects and interactions with TWI over the years, including day-today support on conventional welding and NDT and, increasingly, on research and development in additive manufacturing particularly.

Four years ago, Tanya joined Thales' underwater systems business and saw quite a different set of materials and environments from previous jobs.

Through her role within TWI's Technical Committee, Tanya has noticed many common challenges with industries such as nuclear and wind energy, and is passionate about finding ways we can work together to all benefit from new technologies.

Tanya Sabin
Senior Materials Engineer, Thales UK

Andrew is a lead for the Materials and Processes in Metallics and Metals Bonding team at GKN Fokker. After graduating from the 3ME-Faculty of Delft University of Technology in the Netherlands, he completed a PhD in aluminium extrusion, focusing on the improvement of the mechanical properties of hollow parts for structural applications.

Throughout his career spanning over 30 years, he has held several functions in the light metals industry, supporting alloy development, metals processing optimisation and product development for various industries, such as transportation, including automotive, rail, aerospace and civil infrastructure.

Andrew has closely interacted with universities and research institutes, engaging in collaborative projects, improvement of light metals manufacturing processes and the realisation of innovative high-performance products.

Andrew den Bakker
Lead Materials & Processes, Metallics and Metals Bonding, GKN Fokker

Joe joined Boeing Research and Technology (BR&T) as a Materials and Process Engineer after completing his PhD at the University of Manchester four years ago.

During his time at Boeing, Joe has developed and lead a portfolio of wire feed additive manufacturing research projects for BR&T – Europe, and recently joined the Manufacturing Committee at TWI as Vice-Chair.

He has a particular interest in developing new technologies for improving efficiency and sustainability while reducing the cost of manufacturing processes.

Joe Fixter
Materials Process and Physics Engineer, Boeing

Digitalisation & Data

		Page
34241	Artificial Intelligence for NDT Scanning of Unknown Geometries using Collaborative Robots	14
35239	Development of Digital Twin Technology as a Demonstrator for Real-Time Integrity Assessment of Crack Growth in Tensile Specimens	15
35254	CAM DED – A Review of Directed Energy Deposition CAM Tools to Help Industrial Decision Making	16
34765	Development of Coded Excitation Techniques for Non-Metallic Pipes Inspection	17
34727	Techniques for High Temperature Ultrasonic Inspection of Arc Welding	18
35258	In-Process Detection and Non-Destructive Testing of Electron Beam Weld Imperfections	19
35241	Integrating Probabilistic Approach into British Defect Assessment Procedure	20
34847	Fracture Toughness in Aggressive Environments: Effect of Crack Monitoring Techniques on Test Results	21
35268	Development of Structural Health Monitoring Technology for Pressure Containing Pipelines using Guided Waves and Acoustic Emission	22

Net Zero

33552	Assessment of the Durability of Abhesive Surfaces	23
35255	Long Term Behaviour of Polymeric Liner Materials/Coatings in Hydrogen Service	24
34250	Thermoplastic Materials Compatibility for Hydrogen Service	25
34741	Development of Friction Stir Welding for Hydrogen Fuel Storage Tanks	26
35410	Hydrogen Embrittlement Reduced by Oxygen and Moisture (HEROM)	27
35264	Enhanced Understanding of Degradation Environments that Develop at Metal/Non-Metal Interfaces for Carbon Capture, Utilisation and Storage Environments	28

New Materials & Circular Economy

33541	REACH Compliant Aluminium Pre-Treatments	29
34729	Establishing Assessment Methods for Determining Safe Service Limits of High-Temperature Materials in Extreme Environments	30
34742	Development of Leak-Before-Break Hydrogen Storage Composite Pressure Vessels with Polymeric Liner	31

Smart Manufacturing

34788	Optimising Arc-Based Additive Manufacture using Fracture Mechanics Approaches	32
34745	4D Printing for Field Morphing Structures (AMorph)	33
35476	Effortless Support Structure Removal (ReMove) for Metal 3D Printing	34
35253	Automated Quality Control of Wire Arc Directed Energy Deposition Build for Smart Manufacturing	35
34730	Joining of Additively Manufactured Materials	36
34793	Coaxial Wire Additive Manufacturing Processes and In-Line Monitoring Tools	37
34718	Automation of Composite and Hybrid Joining Process	38
35283	Internal Bore Coatings for Applications in Corrosion and Hydrogen Environments	39

TWI CRP RESOURCES AT YOUR FINGER TIPS...

The project summaries can also be accessed by visiting twi-global.com/crp or **scan the QR code.**

Artificial Intelligence for NDT Scanning of Unknown Geometries using Collaborative Robots - 34241

Project Type	Conventional
Project Due Date	December 2023
Technical Committee	Engineering
Industrial Mentors	BAE and Rolls Royce

Project Leader: Calum Hoyle, Senior Robotics Engineer, Advanced NDT, TWI

Industry Sectors

Aerospace

Surface Transport

Power

Objectives

- Review current artificial intelligence (AI) techniques for goal-oriented action planning and their fields of applications. This is to include currently implemented robotic and self-driving car applications using deep-learning networks. The suitability of these approaches to be used with cobots will be determined.
- Integrate a phased array probe as an additional sensor tool with a cobot which has highly sensitive force/torque sensors.
- Develop algorithms that can correct the motion and orientation of a cobot based on force and ultrasonic feedback.
- Implement search algorithms to ensure full surface coverage as needed by the application with the cobot control software.
- Demonstrate the benefits and drawbacks of the developed system through a parametric study based on industry provided samples.

Project Outline

The project will look at how artificial intelligence can be used in conjunction with ultrasonic sensors and cooperative robots (cobots) to perform NDT of unknown complex geometries. The use of force/torque sensors means that the robot can detect when a probe touches a surface. The feedback from these sensors can measure forces and torque in three dimensions, which allows the robot to control both position and orientation. These data can be utilised to follow a surface, alleviating the need to know the full surface geometry. NDT inspections often require a probe to cover a certain area, such as the heat-affected zone around a weld. Deciding how to cover this area is a task that is well suited for artificial intelligence (AI) as it becomes an exploration problem.

Ultrasonic phased array probes have been accepted as state-of-the-art in industry due to their enhanced imaging capabilities. By using a phased array probe (with a wedge) on a cobot, it is possible to incorporate this additional sensory information to align the cobot with the surface, in order to ensure the capture of adequate data. Combining force/torque sensing with ultrasonic feedback will lead to an automated scanning system that is optimised for NDT of complex surfaces.

The project will investigate an aspect of AI known as goal-oriented action planning. Goal oriented AIs have been used for a number of years in computer games and have recently been implemented in self-driving cars. The goal(s) are typically defined at a high level, such as “reach point B from point A”, allowing the AI to make a number of decisions about how to reach that state autonomously. The project will incorporate this type of AI approach to ultrasonic inspection of complex geometries using cobots.

To ensure a well-defined problem space, the project will be limited to the inspection of complex weld geometries, supplied by industry partners, using a cobot with a phased array probe. This will ensure that the number of parameters is kept at a reasonable level while algorithms and AI approaches are developed. It is envisaged that the project will result in actual, on-site trials to determine the applicability of the developed system in real-world scenarios.

Benefits to Industry

Deployable automated techniques are required for in-service inspections as well as at the manufacture and assembly stages. The drive toward industry 4.0 requires that digital automated systems are developed to provide feedback to design and manufacture and to enable the creation of digital twins. In addition, industry needs to leverage the power of AI to decrease set up times and ensure good data quality.

The capability developed in this project will enable industry to employ cooperating robots to undertake NDT and other tasks at manufacture and in-service without the need for a dedicated safety cell.

Development of Digital Twin Technology as a Demonstrator for Real-Time Integrity Assessment of Crack Growth in Tensile Specimens - 35239

Project Type	Cross-cutting
Project Due Date	June 2024
Technical Committee	Engineering
Industrial Mentors	Navantia and ARAMCO Tech

Project Leader: Stephen Grigg, Condition Monitoring Specialist VAL at TWI

Industry Sectors

Electronics and Sensors

Automotives

Medical Equipment

Objectives

- Develop a digital twin demonstrator for real-time integrity assessment of crack growth in tensile specimens.
- Develop a decision making tool to prevent critical failure.
- Integrate sensing technologies with digital technologies for proactive control of operations.

Project Outline

This CRP aims to build a demonstrator of a digital twin technology by leveraging currently existing technologies across TWI and articulate them so that the digital twin provides an effective, proactive, real-time, decision-making tool for predicting critical damage to structures.

The selected application are thermosetting composite (RTR) coupons subjected to tensile loading. The coupons will be monitored with acoustic emission (AE) technology which will detect and localise damage progression. The AE signals will be interpreted live and will feed a previously calibrated finite element analysis (FEA) model of the coupons. The FEA model will establish the current state of stress and predict future damage propagation. In case of predicted critical damage, the FEA model will alarm and communicate the test rig to stop the tensile load application hence preserving the structural integrity of the coupon. Computed Tomography (XCT) will be used as an independent benchmark technology so as to support and validate the AE data interpretation and FEA model assumptions. The project concept is shown in the figure below:

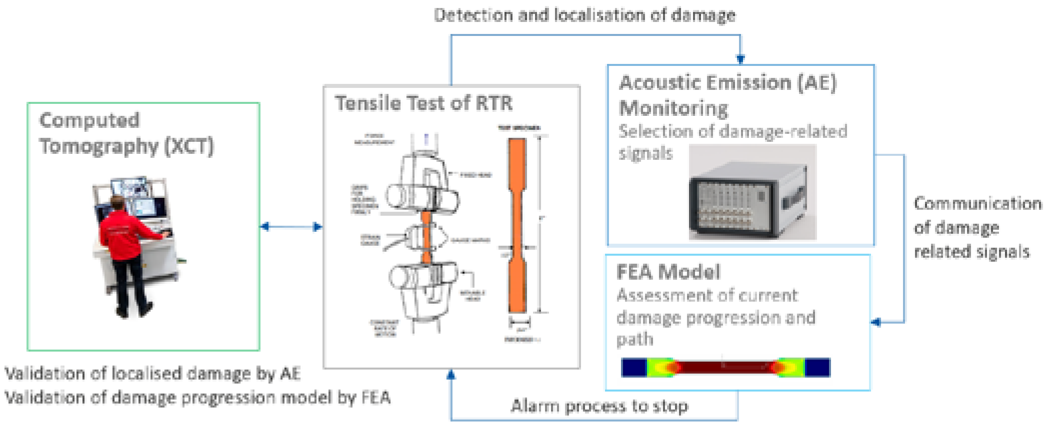


Figure 1 Decision tool concept

The development of the digital twin will be executed in accordance to DNV-GL-RP-A204 "Qualification and assurance of digital twin" for consistent development and future technology qualification.

Benefits to Industry

- Proven demonstrator of digital twin technologies will enable its development and tailoring to more advanced and sophisticated applications from TWI's Industrial Members.
- Increased understanding in damage mechanism propagation and how to conduct their early detection and localisation with monitoring technologies.
- Tested and verified algorithms for analytical damage prediction which can be applied to relevant structures and assets.
- Development of a communication tool which will enable the real-time decision-making.

CAM DED – A Review of Directed Energy Deposition CAM Tools to Help Industrial Decision Making - 35254

Project Type	Conventional
Project Due Date	December 2025
Technical Committee	Manufacturing
Industrial Mentors	Rolls Royce, Boeing and Sulzer

Project Leader: Jhonattan Gutjah, Project Leader LAM at TWI

Industry Sectors

Defence Power Aerospace

Objectives

This project aims to provide an impartial review of computer aided manufacturing (CAM) software tools, disconnected from any commercial interests, and conducted by directed energy deposition (DED) users and CAM software developers at TWI. This will be mentored by TWI Industrial Members to define requirements and expectations, and supported by software developers to offer expertise on software capabilities and access to software, training and digital tools in place. The following objectives are initially assigned:

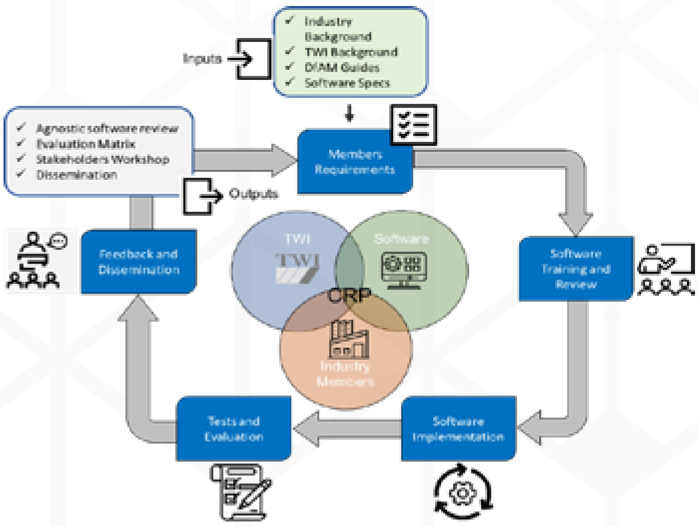
- To define industry requirements and expectations for DED CAM software; underpinned by the creation of a matrix to capture key capabilities of the chosen software providers.
- To test and evaluate the software features against the defined reference part(s) (which incorporates DfAM of ASTM F31413 Guide on Design of Additive Manufacturing on DED technology) e.g. Boss on a curve, single-pass wall, dual-pass wall, impellers blade, etc.
- To compile the results to feedback and disseminate the evaluation and developments among members in an accessible format including the decision matrix and accompanying report.

Project Outline

To achieve the project objectives, 5 main work packages were planned, as follows:

Work Package 1 – Industry Requirements and Expectations
Work Package 2 – Software Training and Review
Work Package 3 – Software Implementation
Work Package 4 – Tests and Evaluation
Work Package 5 – Feedback and Dissemination

This is summarised on the schematic:



As outcomes, the project aims to deliver:

- Workshops for the CRP stakeholders
- Software installed at TWI and commissioned on at least one DED system (e.g. gantry, robot)
- Reference test geometry based on ASTM F3413
- Evaluation matrix of DED CAM tools

Benefits to Industry

A review of CAM software solutions for directed energy deposition is the key topic of this project. The TRL level of commercial software tools differ among the providers, usually between TRL 5 to TRL 9. The large range is strongly dependant on the match between the software and the technology and application using it. Seeking a perfect match of software with technology (not just DED) is a problem for Members and multiple sections within TWI that operate industrial manipulation equipment. This CRP will advance TRL levels of multiple industries and TWI sections through offering an informed approach to software selection for different additive manufacturing (AM) and surfacing technologies. The correct software selection will enable an eventual jump from TRL7 to TRL9 for applications in, for example, repair and AM of large scale components.

For TWI Industrial Members, the main benefits are:

- The knowledge gained through exploitation of multiple CAM tools focused on DED applications will help Members' decisions around AM technology and software implementation. The decision matrix, outcome of project, will support the industry on this aspect.
- The project results will allow Members to access the state-of-the-art in terms of DED CAM solutions. This will facilitate technology transfer to Members, and thus ultimately more rapid adoption of AM.
- The development of Single Client Projects (SCPs) will be enhanced in terms of quality, cost reduction and time optimisation, for the benefit of Members and TWI.

Development of Coded Excitation Techniques for Non-Metallic Pipes Inspection - 34765

Project Type	Conventional
Project Due Date	December 2024
Technical Committee	Engineering
Industrial Mentors	Exxon Mobile and BP

Project Leader: Owen Rees-Lloyd, Senior NDE Project Leader AEM at TWI

Industry Sectors

Oil & Gas

Construction

Power

Objectives

The overall aim of this project is to develop an ultrasonic inspection technique which can enhance the signal to noise ratio in highly attenuating materials, and validate the technique with samples of interests to the industries. More specifically this project has the following objectives:

- Develop an ultrasonic technique that is able to measure the thicknesses of the pipe and of each layer, and demonstrate it on the selected TCP and RTP pipes
- Develop an ultrasonic technique that is able to detect flaws like delamination, thinning, fibre-breakage etc in the pipe and demonstrate it on the selected TCP and RTP pipes
- Produce a user friendly interface to acquire and analyse the data.

Project Outline

Non-metallic pipes have been gaining popularity in the oil and gas industry in recent decades due to the advantages of their corrosion resistant properties, strength to weight ratio and cost. They are typically made of reinforced thermoplastic materials commonly known as reinforced thermoplastic pipe (RTP) or thermoplastic composite pipe (TCP). Up to now, there is no standard governing the NDT inspection of such pipes. Even design standard like 'DNV-GL-F119 Thermoplastic Composite Pipes' allows the NDT inspection to be replaced by well-documented production controls due to the lack of effective NDT methods.

There are important design variations in non-metallic pipes, as compared to their metallic counter-parts, and the flaw types are a lot more complex too. That is also why there is no NDT strategy that can cover all the failure modes. In the past, micro-wave inspection and digital X-ray have achieved good results in covering a number of flaws with dimensions of a few mm. However, both techniques require costly instrumentation, with one unit typically costing ~£200k up to a few hundred thousand pounds. In addition, radiography techniques demand stringent site safety requirements.

In the field of non-destructive testing of metallic structures, the trend is shifting from radiography to ultrasound, which is inherently safe from radiation and usually uses much cheaper instrumentation. A conventional ultrasonic inspection device costs only a few thousand pounds; even an advanced phased array unit is significantly below a hundred thousand pounds. Over the past decades, ultrasonic inspection has replaced most of the radiography inspection in the oil and gas industry for post-manufacturing and on-site inspections. Comprehensive international standards are also available to govern the use of ultrasonic inspection in sentencing metallic structures.

This project focuses on coded excitation technique in ultrasonic inspections of TCP and TRP pipes. With this technique low energy input (10V) is able to achieve an equivalent signal-to-noise ratio to a conventional 220V energy input in metallic structures. In this project, various samples will be supplied both by the sponsors and internally through the ACA section. The project will start by establishing the optimum signal-to-noise ratio in the plastic pipe samples using various coding, and then correlate the thickness degradation to the detected signals. If successful, the project will proceed to look at other failure modes like delamination, cracks etc.

Benefits to Industry

This project will provide an effective, inherently safe and affordable technique to inspect challenging materials with high attenuation.

Techniques for High Temperature Ultrasonic Inspection of Arc Welding - 34727

Project Type	Conventional
Project Due Date	January 2024
Technical Committee	Engineering
Industrial Mentors	Framatome, Navantia, and Westinghouse

Project Leader: Kai Yang Senior Project Leader, Technology, NIS at TWI

Industry Sectors

Power Oil & Gas Manufacturing

Objectives

This project aims at investigating the application of machine learning methods and conventional signal processing techniques to adaptively address the adverse impacts of high temperature during welding process. To achieve this goal, a test rig and prototype system will be developed to facilitate experiment and ultrasonic inspection under 450°C. Ultrasonic A-scans and transient temperature profiles are to be recorded for post analysis and algorithm development.

Project Outline

The project consists of three work packages, namely:

Work Package 1 – Literature research on state-of-the-art. The aim for this work package is to develop knowledge regarding the state-of-the-art of correction methods for high temperature UT applications.

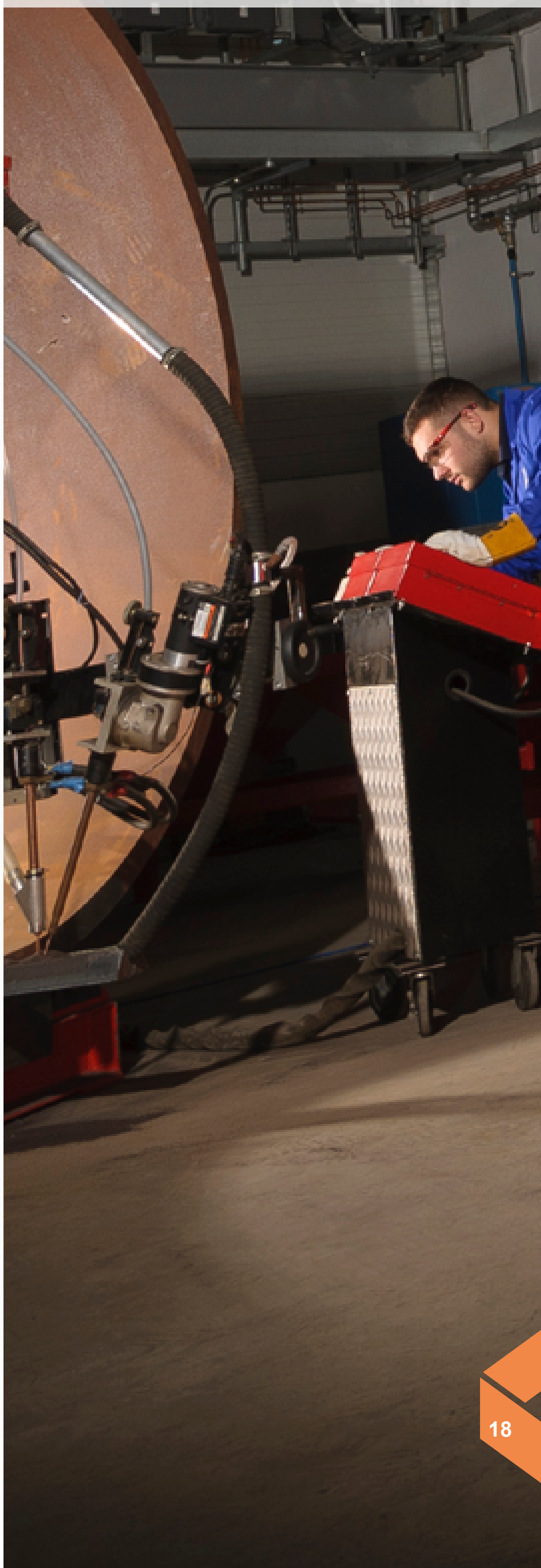
Work Package 2 – High temperature experiment and data collection. In this work package, current development of the high temperature test rig will be improved in terms of couplant delivery, leakage prevention and data collection system optimisation, to enable high temperature UT capabilities for arc welding, the targeted temperature will be 450°C.

Work Package 3 – Comparative study of correction methods for high temperature UT application. In this work package, comparative study will be conducted using the UT data collected from the experiment. Both machine learning techniques and conventional image processing techniques will be investigated to develop an adaptive algorithm to address the high temperature impacts on the UT data.

Benefits to Industry

Upon successful delivery of the project, the expected benefits include:

- Reliable ultrasonic inspection techniques for Arc Welding at elevated temperature conditions
- Early detection of indications will reduce cost, improve quality and assist scheduling
- A prototype system capable of ultrasonic inspection at high temperature which is able to be adapted for validation and further development work
- Investigation results on using Machine Learning technologies for Non-Destructive Evaluation.



In-Process Detection and Non-Destructive Testing of Electron Beam Weld Imperfections - 35258

Project Type	Cross-Cutting
Project Due Date	June 2024
Technical Committee	Engineering
Industrial Mentors	CVE, MTU Aero, and UKAEA

Project Leader: Channa Nageswaran, Consultant NIS at TWI

Industry Sectors

Nuclear power

Aerospace

Renewable

Objectives

- Identify and test suitable ultrasonic testing techniques for assessment of electron beam welds both at ambient and in-process conditions.
- Establish impact of changes in welding conditions in-process on weld quality outcomes as determined by inspection according to governing standards.
- Outline suitable acceptance criteria for weld quality based on standards with the possibility to build live online feedback between inspection and welding for the future generation of electron beam welding systems.
- Demonstrate the capability over a selection of materials.

Project Outline

Electron Beam (EB) welded specimens will be generated by TWI's EB section with changes in in-process conditions within an agreed spectrum. The specimens will then be examined by a range of ultrasonic testing (UT) techniques that are operable on surfaces at both ambient and elevated temperatures. The inspection reports will aim to provide information in a form that will allow for the quality of the EB welds to be assessed according to BS EN ISO 13919-1 (Electron and laser-beam welded joints – Requirements and recommendations on quality levels for imperfections.). Based on this information correlation between welding parameters and product quality outcomes as determined by inspection and quality standards can be established. The outcomes of this proposed project will enable future generation of electron beam welding systems that can monitor the weld during fabrication and create a live online feedback between inspection and welding to maximise product quality.

Benefits to Industry

Reliable non-destructive identification of discontinuities due to out-of-process transients in EB welds is required during welding. It has been identified that an industrial need is present for the ability to correlate between detected flaws in metallographic specimens and in-process data. Recent advancements in ultrasonic testing technologies within TWI have already demonstrated capability to detect the type and size of defects common to EB welding. By applying these advancements to the inspection of EB welds, the industrial need can be met. Furthermore, by conducting the inspection during the welding process, correlation can be made between detected flaws and in-process data. The UT technique will also be applicable to a wide range of metals, including titanium and zirconium alloys.

Integrating Probabilistic Approach into British Defect Assessment Procedure - 35241

Project Type	Cross-Cutting
Project Due Date	September 2025
Technical Committee	Engineering
Industrial Mentors	Framatome, Navantia, and Westinghouse

Project Leader: Yin Jin Janin, Principal Project Leader, Technology FIM at TWI

Industry Sectors

Power Generation and Renewable Energy

Shipbuilding and Marine

Oil & Gas

Engineering and Fabrication

Objectives

- Establish a probabilistic fracture management (PFM) procedure in BS 7910, and a new functionality in CrackWISE® that is technology-neutral.
- Initiate the integration of a probabilistic engineering critical assessment (ECA) approach into the BS 7910 flaw assessment procedure
- Establish a probabilistic residual stress treatment approach in line with BS 7910
- Address the gaps in flaw assessment procedures related to thick-section welds and associated residual stress
- Determine the significance of other input parameters, especially the effect of in-service degradation on reliability of safety critical components
- Optimise PFM models that could account for most significant variables such that the results become comparable to those in recommended practices and design codes.

Project Outline

In 2019, CRP 32878 was initiated to understand the methods for assessing the reliability of safety-critical structures in a fully quantitative way. TWI Industrial Member Report 1136/2020 examined in detail two methods, i.e., risk-based inspection and fracture mechanics, typically used in determining reliability of a given structure. Various case studies were employed to demonstrate the differences between these two methods, as well as the possibility of integrating both. The first deliverable of CRP 32878 was described in TWI Industrial Member Report 1136/20201. The other three reports are currently under peer-review.

The previous project has demonstrated that the use of PFM is a viable alternative, the main advantage of which is that the inputs (such as initial flaw size) can be tailored to the details of a particular components, allowing a direct estimate of probability of failure (POF). There remains a need to continue the efforts to rationalise and ensure both methods become fairly comparable. For these reasons, further investigation is required to:

- Determine the significance of other input parameters (besides material properties) on POF.
- Optimise PFM models that could account for most significant variables such that the resultant POF becomes comparable to those in recommended practices and design codes.

This project will aim to explore the following:

- State of the art review on existing PFM procedures
- Application of probabilistic treatment of as-welded and post-weld heat-treated residual stresses in a BS 7910 context
- Evolution of material properties in particular the effect of aging and change of service (for example from natural gas to hydrogen transmission)
- Loading occurrence frequency/utilisation rate
- Residual stresses and flaws in narrow gap welds e.g. electron beam (EB) and narrow gap TIG
- Rationalisation of BS 7608 fatigue design curves using PFM

Benefits to Industry

A probabilistic treatment of an integrity assessment can bring financial and operational benefits by offering a better understanding the risks associated with an asset and allowing safer operation. The probabilistic treatment of integrity assessments is also an opportunity to optimise the design and operation of an infrastructure. This project will increase the body of evidence to support the adoption of probabilistic structural integrity assessments. This project could significantly enhance the ability to perform probabilistic assessments in accordance with the BS 7910 (CrackWISE®) procedure that is technology-neutral, and could also inform the development of other structural integrity procedures. In addition, the examination of residual stresses and flaws in narrow gap joints such as electron-beam, will help remove some of the uncertainties in adopting the more advanced welding process. This project will examine the available evidence and develop guidance for the narrow gap welding application. The study on material performance of modern pipeline construction for emerging transition from natural gas to gaseous hydrogen applications will be beneficial in supporting the global agenda on this and demonstrate the feasibility of such applications.

Fracture Toughness in Aggressive Environments: Effect of Crack Monitoring Techniques on Test Results - 34847

Project Type	Conventional
Project Due Date	December 2023
Technical Committee	Engineering
Industrial Mentors	OneSubsea

Project Leader: Fokion Oikonomidis, Senior Project Leader, Technology FIM at TWI

Industry Sectors

Oil & Gas

Objectives

- To investigate the effect of testing techniques (DCPD and unloading compliance) on fracture toughness results generated in aggressive environments
- To investigate the effect of K-rate on fracture toughness results generated in aggressive environments with DCPD technique

Project Outline

There is an industry requirement to generate accurate fracture toughness data in aggressive environments for engineering critical assessments. The use of clip gauges in aggressive environments limits the range of tests performed by TWI's world-leading environmental testing laboratory. As an ever-growing demand to go deeper for oil, test environments are becoming more severe, meaning that high temperature and high-pressure autoclaves are required that cannot accommodate a clip gauge. Therefore, TWI is developing the Direct Current Potential Drop (DCPD) approach further and is performing a detailed comparison study to properly understand if the load line displacement indirect estimations are within the level of accuracy suggested by the testing in air standards.

This CRP is investigating the effect of the crack monitoring testing methods (DCPD and unloading compliance) on fracture toughness results generated in deaerated seawater under cathodic protection. In addition, the effect of K-rate in fracture toughness tests is also being investigated in the same test environment.

Benefits to Industry

- Evaluate the degree of accuracy of DCPD compared to using clip gauges in measuring fracture toughness of steel in dearated seawater under cathodic protection;
- Understand the effect of loading rate on the fracture toughness of steel using DCPD in the same aggressive test environment;
- Evaluate the importance of test measurement method and loading rates in aggressive environments, in contrast to what is specified in relevant fracture toughness testing standard in air.

Development of Structural Health Monitoring Technology for Pressure Containing Pipelines using Guided waves and Acoustic Emission - 35268

Project Type	Conventional
Project Due Date	December 2024
Technical Committee	Engineering
Industrial Mentors	AramcoTech, and UKEAE

Project Leader: Dandan Liu, Graduate Engineer VAL at TWI

Industry Sectors

Nuclear power

Oil & Gas

Objectives

- Establish acoustic emission (AE)'s detectability and guided waved (GW) sizing accuracy of pit-to-crack transition and crack propagation stages on specimen 3m long pressurised pipelines.
- Investigate advanced digitalisation techniques for fusing AE and GW data.
- Validate AE and GW results with conventional ultrasonic testing (UT) and fitness-for-service (FFS) assessments.
- Provide recommendations for optimum implementation of AE and GW for SHM of pipelines.

Project Outline

Since the only pressure containing structures that TWI has access to are pipes, the proof of concept will use these. The project will be carried out in two stages.

First stage entails testing a 10 metre long pipe currently located at TWI's graveyard. This pipe was previously inspected using GW as part of PN 25607 therefore the acquisition settings and the procedure is known. This stage will simulate active corrosion using an electrochemical method while continuously monitoring the pipe. AE has been proven to detect corrosion as part of SCP 33526 and CRP 34244. However, the maximum sensor spacing has not been investigated and will be established. GW inspections will be carried out at certain time intervals in order to size the metal loss coming from active corrosion. The corrosion will be simulated at the centre and both ends of the pipe as shown in Figure 1. The objective is to establish the maximum AE sensor spacing for corrosion detection as well as to assess the sizing accuracy of GW and provide recommendations for a potential field implementation.

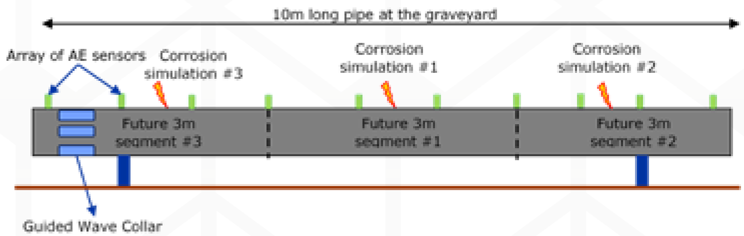


Figure 1 10m long pipe – Active corrosion simulation

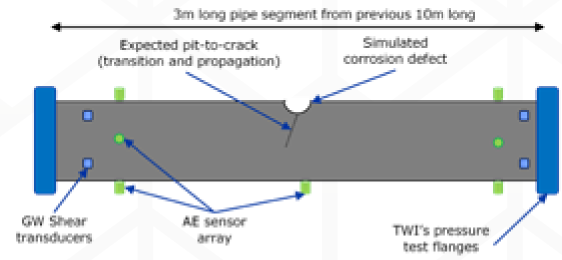


Figure 2 Pressure test of 3m long pipe with AE and GW monitoring

The second stage entails pressure testing 3m long pipe segment cut from the original 10m long pipeline. The 3 metre long segment is selected due to current limitations for pressure testing. The segment will feature a corrosion defect at the centre as shown in Figure 2. The defect will act as a realistic stress raiser and by subjecting it to normal operating pressure, a pit-to-crack- transition is promoted. The pipe will be instrumented with a coarser array of AE sensors in order to localise and track the signals coming from this transition. AE has been proved to detect and localise fatigue cracks as part of PN 33526. Therefore a successful detection and localisation of crack is expected. GW shear transducers will be used in this stage as these are more suitable for sizing cracks. UT scans will be carried out to validate results from AE and GW. In addition, FFS will also be carried out in order to inform about the integrity of the pipe.

The objective of this stage is to assess the accuracy of AE and GW to detect the pit-to-crack transition which is critical to pipeline operators. Three test are proposed and, if successful, an AE alarm will be derived to inform the detection of this stage.

Based on FFS results and confirmed crack lengths by UT, the test will be carried out until failure in order to record the full damage progression with AE and GW. Having AE and GW data of the ultimate stages of the pipe life-cycle will be beneficial for field monitoring pipelines at this critical stage.

Benefits to Industry

- The development of a dual sensing SHM technology based on AE and GW for SHM of pipelines.
- Fusion of dual sensing SHM technology with advanced non-destructive testing (NDT) technology, such as phased array ultrasonics to offer continuous and calibrated monitoring of pipeline degradation.
- Pipeline monitoring technology for use in high radiation and high temperature environments
- Improved monitoring of existing pipelines re-purposed for use in CO2 and hydrogen transportation as part of carbon capture, utilisation and sequestration and the hydrogen economy
- Improved SHM and NDT data analysis for input to future digital twins of pipelines for their lifetime integrity management.
- Possible further development of the technology into other applications such as wind turbine towers and blades, rails and structural I-beams for bridges and cranes.

Assessment of the Durability of Abhesive Surfaces - 33552

Project Type	Conventional
Project Due Date	December 2023
Technical Committee	Materials
Industrial Mentors	Rolls Royce, Boeing, Tremco Illbruck Ltd, Toyobo, Co Ltd, Lambda Energy Ltd, CAV Aerospace, and GKN Aerospace

Project Leader: Tamoor Masood, Senior Coatings Engineer NPT at TWI

Industry Sectors

- Aerospace
- Electronics and Sensors
- Power
- Medical
- Surface Transport (Automotive, Marine, Rail)
- Plastics and Composites

Objectives

- Further development of a rapid coating assessment methodology.
- Utilise the new assessment criteria for durability evaluation of repellent surfaces to compare commercial non-stick coatings on aluminium alloy, titanium alloy and glass.
- Identify the modes of failure of the repellent surfaces as a function of substrate.
- Extend the assessment criteria methodology to include erosion and photochemical damage.

Project Outline

Previous work has developed a new approach to the assessment of the durability of repellent surfaces. This approach used a multi-variate analysis method to define a figure of merit based on considerations of surface roughness, surface energy and retention of these key characteristics under abrasive and aggressive chemical conditions. The measured properties of candidate coatings and surface treatments are measured using standard methods and protocols under this approach. The retention of the key performance indicator, i.e. repellence, as a function of exposure to a range of harsh mechanical and chemical conditions can then be determined. The normalised performance data are plotted in the form of a radar diagram.

This approach bridges the gap that currently exists between measurement of individual properties (repellence, abrasion resistance etc) and long-term functional assessment. It also enables a more rapid comparative assessment between candidate coatings and surface treatments and so can be used to screen candidate coatings for longer term field trials.

Previous work focussed on coating formulations developed at TWI on aluminium Q-panels. The proposed programme of work will expand and extend this approach. In addition to candidate TWI coatings, commercial hydrophobic (fluorocarbon and hydrocarbon) coatings and silanes will be applied to Ti-6Al-4V, 2XXX series aluminium, and glass. These substrates are representative of the materials used in the aerospace and solar photovoltaic industries.

Benefits to Industry

The project will establish a more holistic and accelerated test methodology than conventional functional assessment. This will enable industry to make better selection decisions and to validate these more rapidly than at present.

Long Term Behaviour of Polymeric Liner Materials/Coatings in Hydrogen Service - 35255

Project Type	Cross-Cutting
Project Due Date	June 2025
Technical Committee	Materials
Industrial Mentors	Lloyd's Register, Baker Hughes, Borouge, Rolls-Royce and Shell

Project Leader: Ana Antelava, Project Leader Polymer Science & Engineering NPT at TWI

Industry Sectors

Power | Energy | Engineering and Fabrication | Oil & Gas | Plastics and Composites

Objectives

- Conduct a comprehensive literature survey and produce a detailed review on the materials challenges relating to existing infrastructure. This review will identify the potential benefits of using coating and liners to reduce the amount of adsorbed hydrogen at the steel surface and the challenges associated with their implementation.
- Develop test procedures for evaluation of coatings and liner materials on exposure to hydrogen service conditions as well as their ability to limit hydrogen permeation and ageing/degradation.
- Characterise a number of selected materials pre and post-exposure to selected testing program to evaluate their performance and determine best performing coatings/liners.
- Understand the effect of hydrogen service conditions on material properties (micro/macro-structure, strength, yield, thermal properties).

Project Outline

One of the most promising approaches to decarbonisation is the transition from fossil fuel based energy generation to the hydrogen economy. The mainstream adoption of hydrogen as an energy carrier will require new networks and storage, as well as integration into the existing gas and electricity networks. Building a dedicated hydrogen infrastructure is associated with significant capital costs and investment. Therefore, blending hydrogen with natural gas or complete repurposing of natural gas network are the preferred options.

The small size of hydrogen molecules and ability to permeate and degrade materials are key considerations in the repurposing/design of existing natural gas infrastructure. The specific material challenges are:

- Embrittlement of metallic components.
- Permeation through the metallic component and degradation of external coatings that causes corrosion of metallic parts.
- Ageing of polymeric materials.

Understanding and improving the compatibility of materials with hydrogen is key in determining whether existing pipe network can be used for hydrogen transport, or whether a dedicated network is required.

The focus of this project will be on the behaviour of coatings and polymeric liners that could be used to facilitate the repurposing of the natural gas network for hydrogen distribution. Compatibility of liners as well as performance of barrier coatings for hydrogen transport is not well understood or tested. A comprehensive survey will be conducted to produce a review on materials challenges in the existing infrastructure and potential benefits and challenges of using coatings and liners to reduce the amount of adsorbed hydrogen at the steel surface. Consideration of retrofit application of these technologies into the existing infrastructure will be given.

Within this CRP project, liner and coatings in hydrogen infrastructure, material challenges, material's resistance to hydrogen permeation, behaviour under operating conditions and test methodologies used for design and qualification will be reviewed. Following a thorough literature review, a number of polymeric liners utilised in non-metallic pipes and coatings for metallic pipe protection will be selected for evaluation of their properties after exposure to hydrogen gas at service conditions. The assessment of materials will be performed through thermal, chemical and mechanical properties.

The results obtained during this programme of work will help identify best practice in polymeric liner/coating selection and qualification protocols for hydrogen transport/distribution applications as well as improve safety of the hydrogen transport infrastructure.

Benefits to Industry

- The obtained knowledge on material compatibility will provide TWI Industrial Members with clear and specific data to support their technology developments in the emerging hydrogen sector and materials testing (TRL9) for industrial applications.
- There are very few studies on polymeric liner and coating behaviour under hydrogen service conditions. However, use of polymeric materials is a cost-effective option compared to other solutions. The results obtained during this programme of work will help identify best practice in polymeric liner/coating selection and qualification protocols for hydrogen transport/distribution application.
- The project results could contribute to the development of recommended practises and standards for materials utilised as liners/coatings for hydrogen environment.

Thermoplastic Materials Compatibility for Hydrogen Service - 34250

Project Type	Conventional
Project Due Date	January 2024
Technical Committee	Materials
Industrial Mentors	Airbus, Ford, Technip FMC, AramcoTech, Borouge and Baker Hughes

Project Leader: Ana Antelava, Project Leader Polymer Science & Engineering NPT at TWI

Industry Sectors

Power

Surface Transport

Construction and Engineering

Polymers and Composites

Objectives

- Develop test methodologies for evaluation of polymeric materials performance on exposure to hydrogen, thermal cycling, UV radiation and moisture.
- Determine the effect of chosen degradation mechanisms on the micro- and macrostructure of the thermoplastics utilised in this study.
- Characterise a number of selected polymers pre and post-exposure to determine the effect of hydrogen, thermal cycling, UV radiation and moisture individually and in a number of combinations.

Project Outline

The use of hydrogen as an energy resource is expected to play an important role in the transition to a low carbon economy. A full understanding of the effect of hydrogen on the behaviour of materials and joints in engineering structures is critical for the safe deployment of hydrogen infrastructure. A wide range of non-metallic materials is used in hydrogen production, transmission, distribution, delivery, and storage. Fibreglass, carbon-fibre, and aramid are commonly used in hydrogen storage tanks. High-density polyethylene (HDPE) and polyphenylene sulfide (PPS) are used as piping or tank liner materials. Polytetrafluoroethylene (PTFE), polyetheretherketone (PEEK), acetal, polyfluoroalkoxy (PFA), Buna-N, and fluoroelastomer (FKM) are some common sealing materials in valves.

This project will focus on the effect of hydrogen on thermoplastics that are used or considered for use in hydrogen service. In hydrogen service these materials may be exposed to pressures up to 15,000 psi (100 MPa) and temperatures from -70°C to +120°C, potentially under thermal cycling conditions. Little research has been carried out to explore the effects of such conditions. A number of representative thermoplastics will be selected for preliminary assessment of the effects of hydrogen, UV radiation, thermal cycling and moisture on their mechanical performance and microstructure.

Based on the outcomes of these individual tests, an appropriate, representative, testing regime will be proposed which combines elements of hydrogen, thermal cycling, UV radiation and moisture exposure into a single programme. The visual and mechanical properties of thermoplastics after this combined regime will be compared with specimens that have been subjected to only one of the tests.

Benefits to Industry

The knowledge gained through a fundamental testing scheme of different environmental conditions will assist industry with material and process selection for products operating in a hydrogen environment. Availability of suitable test facilities and an agreed test regime will allow industry to carry out bespoke testing for the development and qualification of new products, leading to improved performance, reliability, safety and cost reduction.

Development of Friction Stir Welding for Hydrogen Fuel Storage Tanks - 34741

Project Type	Conventional
Project Due Date	December 2022
Technical Committee	Manufacturing
Industrial Mentors	European Space Agency

Project Leader: Pedro de Sousa Santos, Advanced Manufacturing Engineer FFP at TWI

Industry Sectors

Power
Energy
Engineering and Fabrication
Oil & Gas
Polymers and Composites

Objectives

- Establish the feasibility of joining circumferential and longitudinal butt joints in thin-walled aluminium using FSW to manufacture tank liners. Develop FSW as a high quality, robust and reliable alternative to TIG. Improve cost, function and safety of hydrogen storage tanks.
- Outline a new design and manufacturing approach concept for FSW tooling/ jigging to enable large-scale manufacture of aluminium tank liners.
- Remain at the forefront of advanced FSW particularly for hydrogen storage technologies and increase TWIs capability to assist members with enquiries regarding FSW of thin-walled aluminium tanks.
- Progress TWI and its Members' standing in the green economy and the push towards net zero.
- Define appropriate wall thickness, tank dimension and alloys for subsequent projects and demonstrators.

Project Outline

Hydrogen is now recognised as the most promising source of energy to achieve zero carbon emission travel, and is considered as an environmentally friendly source to produce electric power. However, a number of authorities recognise that significant research and development is required to mature hydrogen as the fuel of choice for transportation and power in the first half of this century.

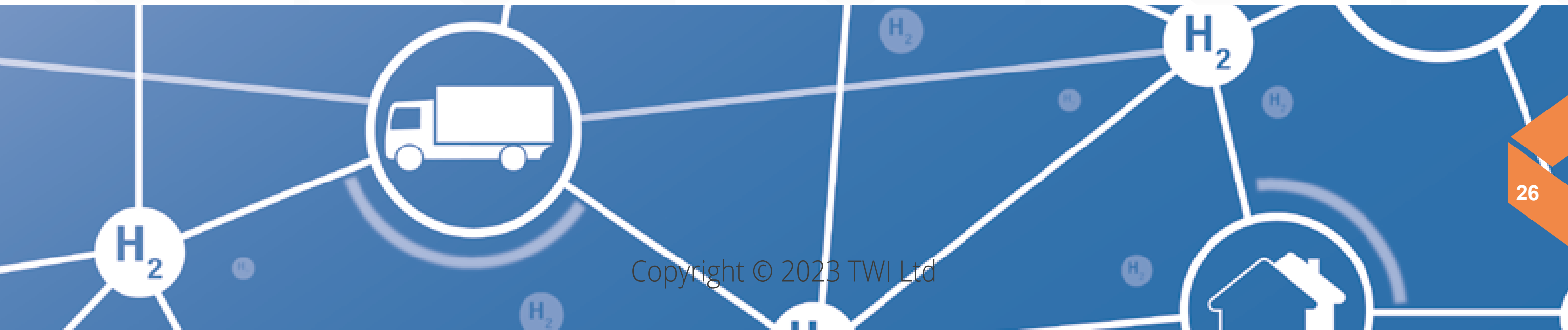
The energy sector is looking to develop transportable hydrogen storage options. Whilst the use of hydrogen as a source of energy has been proven academically, one of the key enabling factors for further industrial uptake is the capability to mass-produce, large-scale, storage vessels. Carbon fibre reinforced polymer (CFRP) vessels lined with thin walled aluminium could offer a lightweight solution for storing hydrogen.

There is an increasing need to develop a reliable, consistent, high quality joining process for thin-walled aluminium liners that can be automated and employed for large-scale manufacture of hydrogen storage vessels. Combined with a reduced aluminium liner thickness, friction stir welding (FSW) could contribute to improve the viability of hydrogen storage solutions by reducing vessel weight, improving joint strength and its damage tolerance, whilst ensuring short and long-term cost savings.

This Core Research Project (CRP) would endeavour to develop the capability of manufacturing thin-walled aluminium liners for lightweight CFRP hydrogen storage tanks, using FSW. While primarily focused on hydrogen storage tanks, the results will have applicability and be scalable for various liquid and gas storage, transport and use. This project is for a continuation of feasibility work which started in Q3 2021 on CRP project 34459.

Benefits to Industry

- This project will work towards enabling broader adaptation of FSW for joining even thinner-walled aluminium liners, for this future high volume market.
- The capability to join thin aluminium sheet using FSW will be developed aiming to deliver consistency and high quality. This is increasing the process maturity, thereby benefiting TWI Members seeking to de-risk and adopt the technology.
- FSW is a machine tool based process giving great possibilities for automation and digital integration, hence helping to mature not only the process, but also its place in the digital/Industry 4.0 domain.



Hydrogen Embrittlement Reduced by Oxygen and Moisture (HEROM) - 35410

Project Type	Conventional
Project Due Date	December 2024
Technical Committee	Materials
Industrial Mentors	Shell, Aker Solutions, Reaction Engines, and ITP Aero

Project Leader: Kasra Sotoudeh, Section Manager, MPC at TWI

Industry Sectors

Oil & Gas - Future Energy

Objectives

- To understand what data are available concerning the effect of oxygen and moisture on the susceptibility of a wide range of steels to hydrogen environmental embrittlement (HEE).
- To propose and carry out a number of tests to help increase our understanding.

Project Outline

- To perform a literature search and review in order to determine the extent of knowledge already available on the effect of oxygen and moisture on HEE and recommend a suitable testing programme.
- Suitable material to be sourced and recommended testing performed.

Benefits to Industry

At present net zero is proving to be a tremendous driver to the decarbonisation of almost everything in our daily lives. There is huge interest in hydrogen as a carbon-free energy vector and yet there is a large gap in our working knowledge of the use of both existing and new assets in hydrogen. Standards organisations and operators are exploring what existing infrastructure or new systems will be suitable for storage and transmission of hydrogen-rich gases. This project aims to provide knowledge to support this transition.

Enhanced Understanding of Degradation Environments that Develop at Metal/Non-Metal Interfaces for Carbon Capture, Utilisation and Storage Environments - 35264

Project Type	Conventional
Project Due Date	December 2025
Technical Committee	Materials
Industrial Mentors	Baker Hughes, Saudi Aramco and Borouge

Project Leader: Amir Shamsa, Design Engineer SCI at TWI

Industry Sectors

- Renewable Carbon Capture, Utilisation and Storage (CCUS)
- Oil & Gas

Objectives

- Further improve understanding of metallic/non-metallic interfaces that develop in high pressure CO2 environments using permeation and corrosion studies.
- Determine corrosion testing methods/design options for reinforcement wires/chords.
- Further develop and upgrade the 3-chamber film permeation cell to incorporate in-situ electrochemical corrosion measurements.
- Develop an understanding of the environments that may develop locally at steel wire surfaces within thermoplastic composite pipes.
- Quantify and monitor the corrosion kinetics of steel wires in-situ as local environments develop.

Project Outline

Thermoplastic composite pipes can be reinforced with steel, enabling extremely high pressure applications such as carbon capture, utilisation and storage (CCUS). However, the static environment which develops locally on the reinforcement wire is unknown and requires further research and study.

This project seeks to create a system capable of determining the species which permeate and their flux, in order to develop an understanding of the environments which may occur, and determine their influence on the corrosion behaviour on typical carbon steel and zinc coated carbon steel reinforcement wires.

This project will build on the capabilities of TWI's recently designed and built 3-chamber permeation vessel by incorporating in-situ corrosion monitoring capabilities using electrochemical methods.

Benefits to Industry

This technology could potentially be used outside of the scope of CCUS to investigate other polymer/metallic interfaces. This may include more traditional oil and gas related environments/products such as flexible risers and enhanced oil recovery. The research will provide information on the following;

- Permeation and polymer performance data for each simulated CCS environments, i.e. permeation data for each impurity/ concentration and pressure/temperature condition.
- Development work demonstrating the optimum method for the study of corrosion processes at polymer/metallic interfaces.
- Corrosion performance data of coated (zinc coated) and non-coated carbon steel reinforcement chords or wires.
- New and improved capability of polymer/metallic interface studies.

REACH Compliant Aluminium Pre-Treatments - 33541

Project Type	Conventional
Project Due Date	December 2023
Technical Committee	Materials
Industrial Mentors	Rolls-Royce, Boeing and Leonardo

Project Leader: Kranthi Maniam, Senior Project Leader SCI at TWI

Industry Sectors

- Aerospace
- Construction and Engineering
- Oil & Gas
- Medical
- Electronics and Sensors
- Power Renewable Energy
- Surface Transport (Automotive, Marine, Rail)

Objectives

- Review available chromium-free conversion coating technologies for aluminium alloys and select suitable candidate processes.
- Procurement and corrosion testing of current Cr-free conversion coating technologies, ranking them using industrially relevant key performance indicators.
- Develop decision support tool to inform and guide industry to suitable REACH compliant surface treatments for selected applications.
- Perform laboratory-based trials to develop innovative treatments for self-healing, chromium-free, anodised coatings.

Project Outline

This project seeks to address the current need for chromium-free aluminium alloy conversion coatings for improved corrosion resistance. There are a variety of chromium-free conversion coatings commercially available, however, there is little impartial information comparing their corrosion performance. The majority of testing that has been carried out has been performed in either an academic environment, not using commercial products, or comparing coating performance solely with Cr(VI) analogues, either chromating or anodising.

This project seeks to provide a clear understanding of the performance of alternative chromium-free conversion coatings with regards to both their corrosion resistance and self-healing capability. Technologies are expected to include phosphating, plasma electrolytic oxidation, zirconium/titanium conversion coatings, cerium conversion coatings, and chromium-free anodising. Results will be used to develop a decision support tool to guide industry in replacing chromium-based technologies.

Benefits to Industry

The project will provide industry with a clear direction as to the most promising chromium-free conversion coating methods, in order to avoid the increasingly restrictive and costly Cr(VI) based approaches.

A decision support tool will be available online to recommend the most appropriate coating technologies as replacements for chromating and chromic acid anodising in different use cases.

Establishing Assessment Methods for Determining Safe Service Limits of High-Temperature Materials in Extreme Environments - 34742

Project Type	Cross Cutting
Project Due Date	June 2024
Technical Committee	Engineering
Industrial Mentors	Arcelor Mittal and Chevron

Project Leader: Dorothy Winful, Senior Project Leader MPC at TWI

Industry Sectors

Power

Oil & Gas

Objectives

- Determine safe service limits for 347H and Alloy 800, against SRC

Project Outline

High-temperature corrosion and cracking are of concern to TWI's key clients and can occur in the oil and gas industry, particularly for refineries, as well as for concentrated solar power (CSP), nuclear fusion and fission and for carbon capture use and storage (CCUS). These industries are crucial to achieving Net-Zero targets. High-temperature failure modes can be very complicated, with contributory factors including long-term aging of materials, the particular environment to which materials are exposed, as well as loading on the component. Additionally, high temperature components have design lives of ten's of years and there are very little data on materials behaviour over such time periods. This is particularly the case for welds and heat-affected zones (HAZs), which are likely regions of failure.

One example of a complex high-temperature cracking and corrosion failure mode, where loading, microstructure and corrosion interact, is stress relaxation cracking (SRC). SRC is known as a failure mode that can occur over moderate service durations in stainless steels and nickel alloys, which are essentially solid solution strengthened but, nevertheless, undergo significant precipitation reactions, during elevated temperature service. Alloys that are known to have been affected include austenitic stainless steels (e.g. 304H, 316H, 321H and 347H) and nickel alloys (e.g. 800/H/HT and 617). SRC failures have occurred in the chemical and petrochemical processing industries, and the phenomenon has also affected power plants made from these materials.

This project aims to utilise a combined approach of modelling, supported by materials testing, to better understand SRC and enable safe service limits for materials operating in complicated and extreme environments to be determined. Such complexity is not just inherent to SRC, but also to a number of other failure modes, including hydrogen embrittlement, strain age cracking etc. Therefore, this project will be a test bed to demonstrate an integrity assessment pipeline, which can be utilised for other materials challenges in the future.

Benefits to Industry

SRC is a long standing issue associated with a significant number of industry failures. A mechanistic understanding of the failure mode has been lacking and this CRP will build on previous project work to better understand the failure mechanism, whilst also providing solutions to avoid failure.

Development of Leak-Before-Break Hydrogen Storage Composite Pressure Vessels with Polymeric Liner - 34729

Project Type	Cross Cutting
Project Due Date	December 2024
Technical Committee	Materials
Industrial Mentors	Saudi Aramco and Ford

Project Leader: Hasan Caglar, Composites Engineer ACA at TWI

Industry Sectors

Power

Objectives

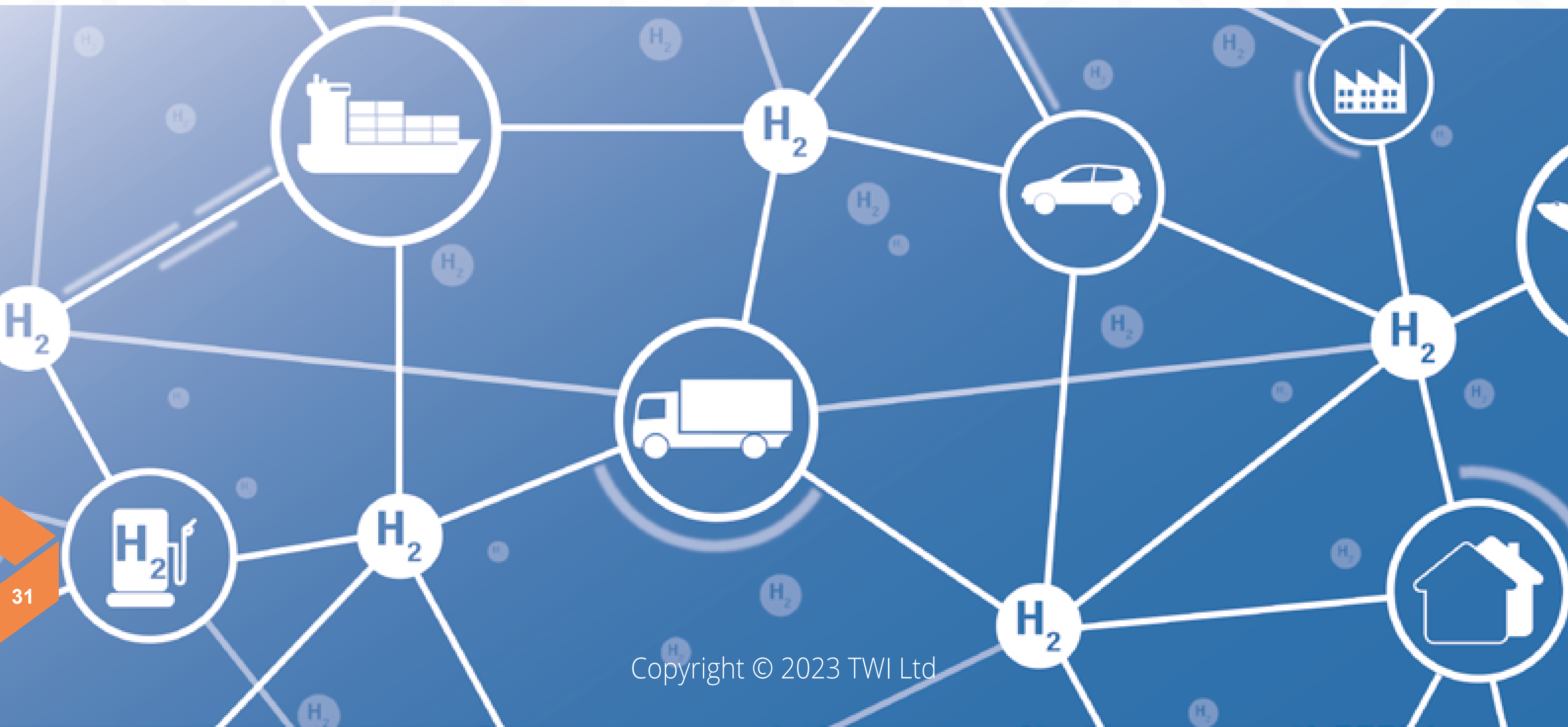
- Select appropriate polymeric liner material for permeation resistance to hydrogen gas
- Determine methodology for application of polymeric liners to composite substrates (joining)
- Develop a numerical model for composite substrate/liner permeation at small scale based on operational requirements, and use the model to identify optimum liner thickness
- Validate the composite substrate/liner permeation numerical model through small scale permeation tests on flat coupons
- Evaluate the performance of fail-safe design scenarios for leak-before-break (LBB) behaviour in composite substrate–liner permeation coupons using the numerical model, taking into account various types, sizes and patterns of LBB design features
- Validate optimum LBB design through small scale permeation tests on flat coupons.

Project Outline

This project addresses this catastrophic failure process through the early stage development of polymer-lined leak-before-break hydrogen storage composite pressure vessels (CPVs), through the implementation of fail-safe design features that permit failure to occur in a controlled, gradual manner.

Benefits to Industry

- The successful validation of this work could be used as benchmark for the development of fail-safe design standards for the wider market of fluids storage CPVs.
- Participation in standards development for composite pressure vessels in the hydrogen economy.



Optimising Arc-Based Additive Manufacture using Fracture Mechanics Approaches - 34788

Project Type	Cross-Cutting
Project Due Date	December 2024
Technical Committee	Manufacturing
Industrial Mentors	Boeing

Project Leader: Lei Xu, Principal Project Leader AWE at TWI

Industry Sectors

- Aerospace
- Power
- Oil & Gas
- Construction and Engineering

Objectives

- Develop arc-based additive manufacturing (AM) processing methods to minimise induced residual stress in the deposit with the aid of numerical modelling and process monitoring.
- Determine the types and distribution of residual stresses that occur within arc-based AM builds.
- Determine the mechanical, fracture and fatigue properties for arc-based AM materials.
- Determine the suitability of current structural integrity assessment methods for arc-based AM material.
- Establish new methods of treating arc-based AM materials in structural integrity assessments.

Project Outline

Arc-based AM, also known as arc Directed Energy Deposition (DED), is gaining significant interest in various industries, as its high deposition rate renders it promising for large load-bearing structures. The structural integrity of such structures is of paramount importance especially in safety critical applications. Residual stress distribution, tensile, fracture and fatigue properties are key inputs into structural integrity assessments, but such properties for arc-based AM materials are not yet well understood. Furthermore, arc-based AM materials may have anisotropic properties, which may require different assessment methods and criteria. These have become the main barriers for the adoption and expansion of arc-based AM into industrial production and structural applications.

The concept is to develop an arc-based AM approach aiming to minimise residual stress through the use of numerical modelling and other digital/smart tools (eg welding cloud systems, vision cameras and laser scanners) to deposit large structural components for residual stress measurement and characterisation of tensile, fracture and fatigue properties.

The data generated from a fracture mechanics perspective will then be used to determine the suitability of current structural integrity assessment methods, which are based on several assumptions on conventional material. Where current methods have been demonstrated to be unsuitable, new assessment methods will be developed to account for the differences between the AM and conventional material (eg material property anisotropy).

Benefits to Industry

The knowledge and capabilities that the project aims to generate will enhance TWI and its Industrial Members' understanding of the relationship between residual stresses and AM processing, thereby feeding into AM process improvements to achieve optimal properties for structural applications. It will contribute to the industrialisation of arc-based AM and accelerate the adoption of AM technologies into the members' production. The concept can be adapted by other AM technologies and material processing processes, eg laser and electron beam AM, cold spray and multi-pass welding.

4D Printing for Field Morphing Structures (AMorph) - 34745

Project Type	Conventional
Project Due Date	December 2023
Technical Committee	Manufacturing
Industrial Mentors	Prof Panagiotis Polygerinos (Hellenic Mediterranean University), Dr Angelos Skembris (Castalia)

Project Leader: Christos Kazasis

Industry Sectors

Aerospace

Health

Objectives

- To explore the availability of smart materials in raw form suitable for additive manufacturing process usage
- To investigate the properties of the printed smart materials for different process parameters and settings
- To manufacture and characterize prototype micro actuators
- To investigate the control methodologies for 4D printed actuators.

Project Outline

4D Printing refers to the fabrication of three-dimensional structures with the added dimension of "time". This pertains to the ability of structures to change shape post-printing (or in the "field") if exposed to predefined environmental stimuli. This dynamic behavior is activated by an external energy input, such as temperature, light, pH, and voltage, among other environmental stimuli.

In addition to the endless possibilities of shapes that 3D/4D printing can offer, it also provides a broad spectrum of sizes. In this project we seek to focus on very small devices also referred to as microrobotics. Unlike regular roboti, which rely heavily on DC/AC motors for actuation and a high number of assembled parts, microrobots are typically based on materials with less complex, straightforward (mostly monolithic) designs. Consequently, 4D printing at a small scale holds very high potential in the field of microrobotics. Traditional microfabrication techniques (cleanroom technology) are highly limited in terms of design, geometries (mainly 2D shapes), and materials selection. By contrast, 4D printing introduces a new level of versatility and complexity into the forms and configurations produced on such a scale; it also allows for a simpler use and integration of a wide variety of smart materials. This renders the design of microrobots with more sophisticated geometries and advanced capabilities, a fast and cost-effective process.

Benefits to Industry

Through this project, we explore the subject of programmable 3D printed robotic micro-actuators using printable smart polymers allowing more compact and inexpensive actuators. The proposed work would put in place advancements in the following fields in 4D printing technology:

- Current knowledge base of smart materials and how their potential could be leveraged for the design of programmable microrobotics actuators fabricated through 3D printing technology;
- The characterisation of such materials towards driving the design and development of controllable smart micro actuators;
- The high-level control of such structures in a controlled and predictable manner.

Effortless Support Structure Removal for Metal 3D Printing (ReMove) - 35476

Project Leader	Antonis Dimopoulos
Project Type	Innovation Center Leveraged
Project Due Date	June 2024
Technical Committee	Manufacturing
Industrial Mentors	GKN Aerospace

Industry Sectors

Aerospace

Automotives

Defence

Biomedical

Objectives

- Investigate and analyse fundamental techniques for effortless support removal.
- Evaluate the various support and process parameters used in metal additive manufacturing (AM).
- Propose optimised support structures capable of producing non-defective parts while printing and post-processing.
- Design optimised support geometries that consume the minimum material required while reducing energy consumption and CO2 emissions.
- Develop a web application for support structures design and generation based on data received through testing and experimentation.

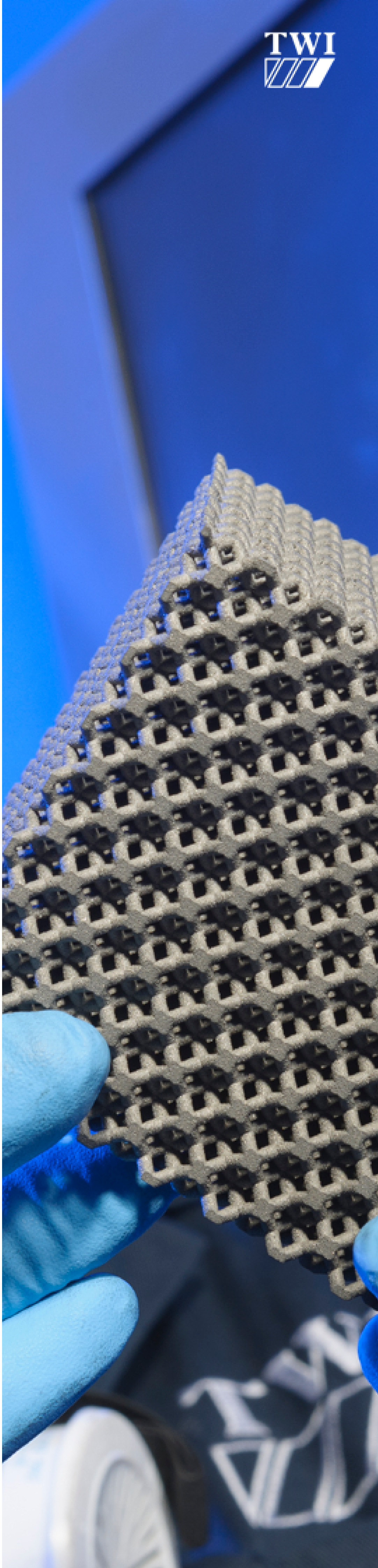
Project Outline

Laser powder bed fusion (LPBF) for metals is one of the most commonly used and rapidly developing AM technologies capable of producing complex, thin, and lightweight components, in contrast to traditional manufacturing, which limits those characteristics. However, because of the nature of 3D printing to fabricate parts in a layer-by-layer manner, this technology faces difficulties with regard to the construction of overhang structures and the warping deformation caused by thermal stresses. In LPBF support structures are always required, thus, producing overhangs without support structures results in collapsed parts while adding unnecessary supports increases the material required and post-processing.

This project will build on top of our expertise on LPBF-based AM, software development, design for AM, and data-driven optimisation to develop a web-based decision support platform for the optimisation of support structures towards ease of removal and zero-defect laser-based parts. The proposed platform will give the user an indication of the ease of removal when designing support structures while maintaining the support volume and the risk of warpage to a minimum.

Benefits to Industry

- Drastically decrease the time needed to remove support structures, resulting in the rapid uptake of LPBF as a production method.
- Reduce the number of parts that get damaged during post-processing.
- Increase the probability of successful printing of parts with zero defects.
- Reduce CO2 emissions via the optimisation of support volume and support placement, resulting in just the right amount of support material.
- Develop a web application to facilitate independent decision workflows for support design and generation, introducing to the industry an innovative tool for effortless, reliable, and sustainable AM.



Automated Quality Control of Wire Arc Directed Energy Deposition Build for Smart Manufacturing - 35253

Project Type	Cross-Cutting
Project Due Date	June 2025
Technical Committee	Manufacturing
Industrial Mentors	Technip FMC, Welding Alloy, Atkin, and Chevron

Project Leader: Capucine Carpentier, Technical Consultant NIS at TWI

Industry Sectors

- Power
- Aerospace
- Surface Transport
- Oil & Gas

Objectives

- Develop a data capture and extraction workflow for process parameter monitoring.
- Improve the existing in-situ inspection system using PAUT, including the interface between the wire arc DED build and substrate and the ultrasonic probe device, and the correction methods for generating high quality A-scan data at high and transient temperatures.
- Extend the application of the ultrasonic system to multilayer builds and complex geometry.
- Establish quality level thresholds for accepting or rejecting data coming from the in-process and in-situ systems.
- Develop an algorithm that collects and synchronises the in-process monitoring and in-situ inspection data.

Project Outline

Wire arc Directed Energy Deposition (DED), also known as wire arc additive manufacturing, is an additive manufacturing process that is gaining popularity in the production of large complex metal components. Wire arc DED technology presents many advantages; cost saving compared to conventional manufacturing methods, such as machining from solid billet, by achieving a significant reduction of material wastage and an increase in time efficiency. Wire arc DED also enables design freedom and can incorporate geometrical features that are not possible to manufacture via conventional means. The process also enables design flexibility and can adapt more easily than conventional manufacturing processes to changing geometrical requirements.

Process reliability and control is crucial for widespread use of wire arc DED in industry. Although process parameters can be optimised via trial and error and the properties of the build can be verified via destructive testing (similar to a weld procedure qualification), this approach is not well suited to an agile on-demand, on-site requirement. Therefore, there is a need to create methods for ensuring process reliability during the wire arc DED build.

This CRP project proposes to build on the knowledge, available from ongoing programmes in TWI to improve the quality and applicability of AM parts, to push the limits of the process parameters and propose tools for applying NDE inspection and monitoring for automated quality control of wire arc DED.

Benefits to Industry

- Increased understanding of materials, processes and on-line monitoring and inspection surrounding AM, but also market leading knowledge and understanding of how these processes could be utilised and reverse engineered into other, more conventional processes.
- Manufacture and availability of high impact information and physical samples relating to AM, to be used at TWI.
- Identification of key research questions in the larger AM, welding, joining, materials and testing research landscape and providing a validated framework for follow on work which is industrially and scientifically valid.
- The output of this programme is to improve quality and applicability of AM parts by generating information to bring the automated digital AM vision one step closer. The ability to create high quality parts with consistent and predictable qualities and to monitor the manufacturing process online reduces post-process inspection burden, thus making AM more cost and quality effective. Additionally, AM can be considered for high value applications where AM is not currently considered suitable.
- There is also added potential for cost saving, quality improvement, or increased productivity through reverse engineering of extended capabilities into existing manufacturing streams.

Joining of Additively Manufactured Materials - 34730

Project Leader	Kandarp Amin, Senior Project Leader, TPT at TWI
Project Type	Cross Cutting
Project Due Date	December 2024
Technical Committee	Materials
Industrial Mentors	Boeing, Baker Hughes, Rolls Royce, and MoD

Project Leader: Kandarp Amin, Senior Project Leader, TPT at TWI

Industry Sectors

- Oil & Gas
- Power
- Aerospace
- Defence

Objectives

- Perform experimental trials on brazing and diffusion bonding of 316L and alloy 718
- Evaluate the integrity of the brazed and DB joints through non-destructive and destructive tests
- Assess the microstructural evolution in the substrate as well as in the joint after the joining process (brazing & diffusion bonding)
- Perform functional tests on the braze joint such as tensile, shear, fatigue and corrosion
- Manufacture two different using selected L-PBF and joining parameters

Project Outline

Metal additive manufacturing (AM) has seen a huge growth in development and adoption in the last decade. However, several problems still persist despite the continuous development. Some of these problems are part size, single material manufacturing, and inability to clear, fully enclosed, internal geometries, among others.

Joining of AM parts offers a number of potential benefits including the possibility to manufacture larger size parts by the joining of multiple components, generation of multi material structures and the manufacture of support free, complex structures with intricate internal geometries.

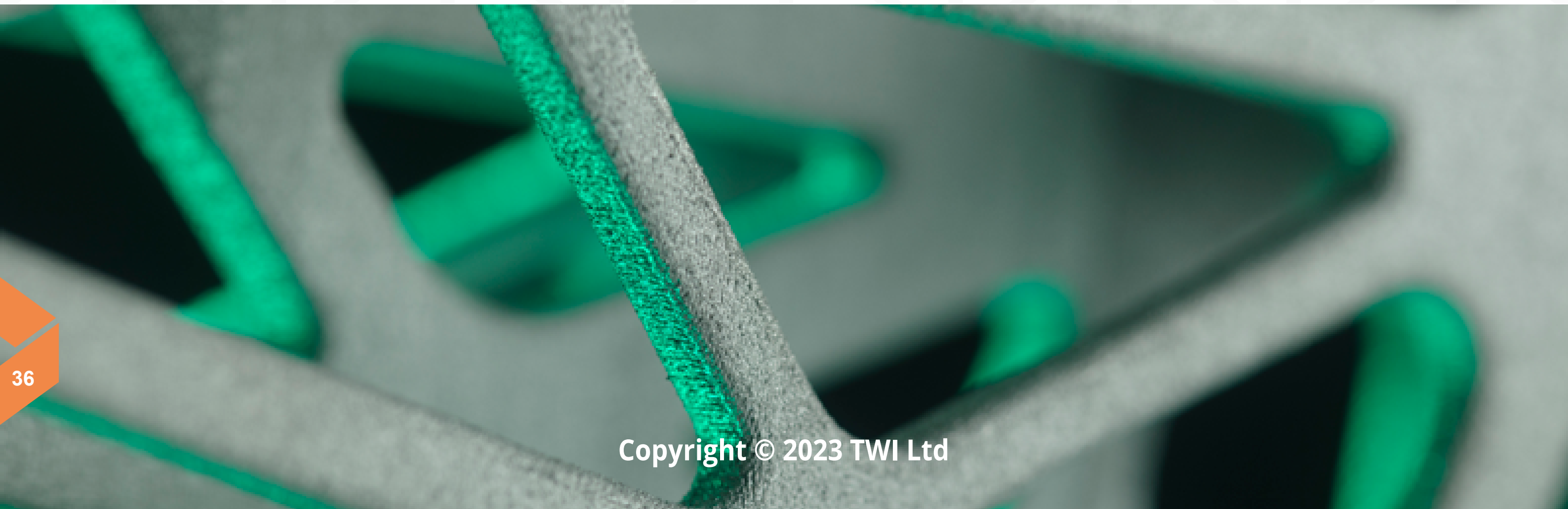
The overarching goal of the project is to understand how laser powder bed fusion material can be joined using solid state joining methods. Specifically, the following themes will be investigated:

1. Joining through brazing with a variety of brazing fillers
2. Joining through diffusion bonding with and without interlayers

Both joining methods are well established for use with conventional materials with a large amount of technical knowhow available. Additionally, they allow the joining of complex geometries with minimal microstructural impact. TWI already has both the equipment and the technical background to successfully investigate and propose joining solutions for these novel materials.

Benefits to Industry

Industry will benefit from this project due to the methods and strategies that will be developed to bypass some of the limitations of AM technology. TWI can add value for industry by expanding knowledge of current joining technologies on novel AM materials.



Coaxial Wire Additive Manufacturing Processes and In-Line Monitoring Tools - 34793

Project Type	Cross-Cutting
Project Due Date	December 2024
Technical Committee	Manufacturing
Industrial Mentors	Boeing and UKAEA

Project Leader: Tom Pinto, Principal Project Leader, Technology EBD at TWI

Industry Sectors

- Aerospace
- Construction and Engineering
- Oil & Gas
- Power
- Equipment, Consumables & Materials
- Surface Transport

Objectives

- Develop an enhanced capability and flexibility for meter-scale additive manufacturing with coaxial-wire directed energy deposition (DED) technology
- Produce benchmarking data and comparison between electron beam (EB)- and laser beam (LB)-DED technology and resultant materials
- Validate in-line process monitoring tools for process control and quality assurance
- Demonstration of advantages and technology potential

Project Outline

Additive manufacturing (AM) can produce parts by adding material layer-upon-layer, this is enabled with assistance of CAD/CAM. AM is often renowned for improving material utilisation, and manufacturing speeds for complex components.

- DED technologies are unable to produce features and geometries as complex as powder bed fusion (PBF), but are generally much faster at adding material and can produce parts much larger >1000cm3. Additionally DED technologies can be used for a wider range of applications including coatings, repair, hybrid/feature addition, and large-scale near-net shape AM
- Wire deposition offers a number of potential advantages over powder deposition
- Higher productivity (5-20x faster deposition rates)
- Cheaper feedstock material (£15/kg cf £60/kg for tool steel)
- High material utilisation (99% vs 85%), and completely free from powder inflicted porosity (though still susceptible to other causes of porosity)
- One of the key barriers to uptake in some of these sectors is quality assurance of components produced by AM

Benefits to Industry

- Offering state-of-the-art innovative services to its Industrial Members
- Enhance staff knowledge & expertise
- Knowledge of performance testing and its results can also be used to generate future business, from customers interested in surface modification and hard-facing coatings for high-value components
- Know-how from this work can be further developed from advanced rotatory coating applications, to repair and freeform AM
- Develop DED AM beyond the current state-of-the-art and increase future member business in AM, particularly in the production and/or repair of high value components
- Knowledge gained will inform members' decisions around AM and process selection. TWI will continue to grow its portfolio of AM and expertise, enabling ideal selection specific member manufacturing challenges
- Machine access, technology transfer leading to more rapid qualification of AM parts.

Automation of Composite and Hybrid Joining Process - 34718

Project Type	Conventional
Project Due Date	December 2024
Technical Committee	Manufacturing
Industrial Mentors	Gestamp U.K. Ltd.

Project Leader: Neelmanee Sarin, Composites Engineer ACA at TWI

Industry Sectors

- Aerospace
- Automotives
- Oil & Gas
- Sporting Goods
- Energy

Objectives

- Develop an automated 3D geometry composites welding capability at TWI.
- Demonstrate the capability by joining the 3D parts in an automated process with an equivalent performance to a current state-of-the-art flat geometry and progress towards a fully automated capacity.
- Create an equivalent performance capability with other TWI technologies i.e; a) Automated robotic NDT (IntACOM™) b) Automated robotic friction processes (RFSSW, CoreFlowTM) c) Automated robotic laser welding (Lasertau) d) Automated robotic thermal spaying.

Project Outline

Industry required robust joining technology for real three-dimensional components, often with complex geometry. Laboratory innovation and prototype joining solution are often generated and evolve in a one or two-dimensional geometry, with simple static jigs or pressure applicators. Although demonstration of the feasibility in the laboratory at up to TRL 3/4 is of value, industry needs to see the technology working on real geometry components.

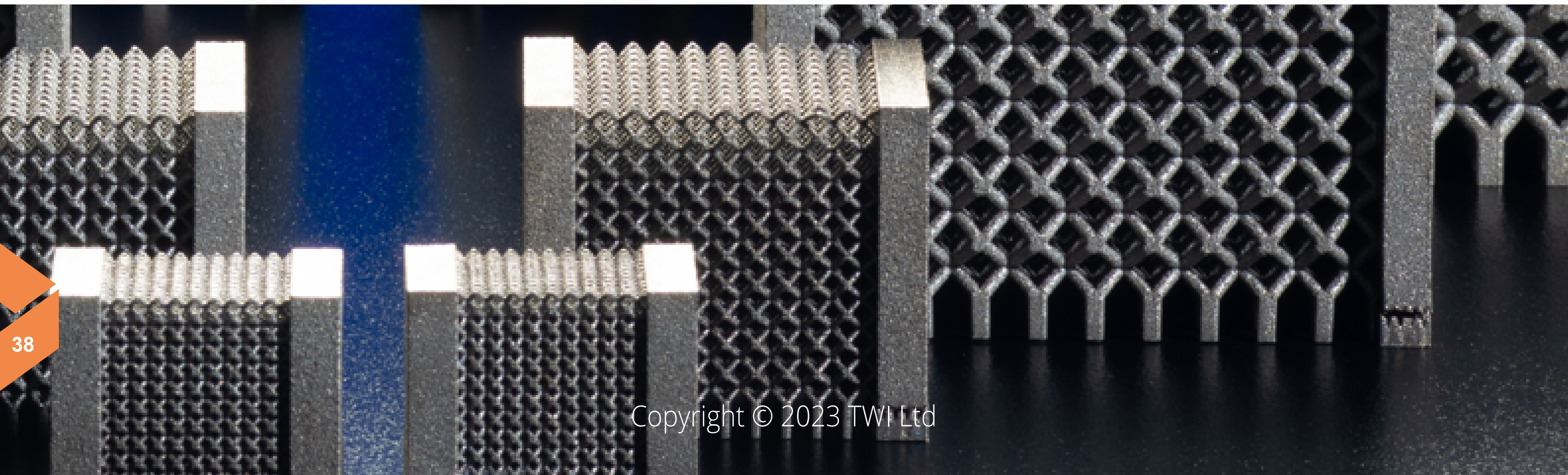
Significant challenges have had to be overcome, not only in the welding steps, but also in the automation. The same challenges are now being faced by the aerospace industry, automotive industry, with the increasing trend for adoption of composites to reduce the mass of vehicles, in the marine industry, where composites in ships are being exploited more and more. Even the oil and gas industry is evaluating welding as a joining approach for non-metallic composite pipes, where thousands of kilometres of reinforced thermoset resin (RTR) pipe is being installed every year.

All these industrial applications will requires significant levels of automation in order to deliver high quality products in high volumes (number of welds per minute).

The aim of the project is simply to progress the composites joining theme towards offering a complete and integrated joining solution to industrial members. The ultimate goal is acquisition of a six-axis robot to facilitate progression of innovation through to TRL 6 'Technology validated in an industrially relevant environment'.

Benefits to Industry

The automation of composite joining processes will help in easier and faster transition and adaptation of TWI wtechnology into industry by progressing up the technology readiness level. The knowledge obtained from the preliminary work will assist in seeding the confidence for building multi-staged automated processes at different stages of product manufacturing.



Internal Bore Coatings for Applications in Corrosion and Hydrogen Environments - 35283

Project Leader	Kylee Yingwei Wu
Project Type	Conventional
Project Due Date	December 2025
Technical Committee	Manufacturing
Industrial Mentors	Subsea7, Onesubsea, and UKAEA

Project Leader: Kylee Yingwei I

Industry Sectors

Power Generation and Energy

Oil & Gas

Objectives

- To build internal bore coating capability for coatings in applications in corrosion and hydrogen environment
- To optimise internal coating processing parameters
- To create a standard characterisation methods to access internal coating quality/performance

Project Outline

In the oil and gas industry, an internal bore coating is usually applied to components (e.g. hydraulics, oil and gas pipeline) to provide corrosion resistance. This is commonly achieved through arc or plasma techniques (TIG, MIG and PTA), alongside laser cladding. However, there are a number of challenges associated with these techniques due to the confined space including; heat build-up, a need for miniaturised optics, limited cooling capacity and excess powder retention and coating build up. Therefore, there is a need to find an alternative solution.

In addition, with the ever-increasing need to shift to renewable and green energy sources, and align with the global political drive to reach net zero by 2050, more and more oil and gas industries are trying to convert their existing infrastructure to accommodate for hydrogen production, storage and transportation. One obvious challenge to that is to solve the hydrogen embrittlement issue in those metal components (e.g. existing gas pipelines, storage tanks), as they will now be exposed in hydrogen environment. A promising and cost-effective solution to that is to apply an internal coating to the metallic components to provide protection under hydrogen environment.

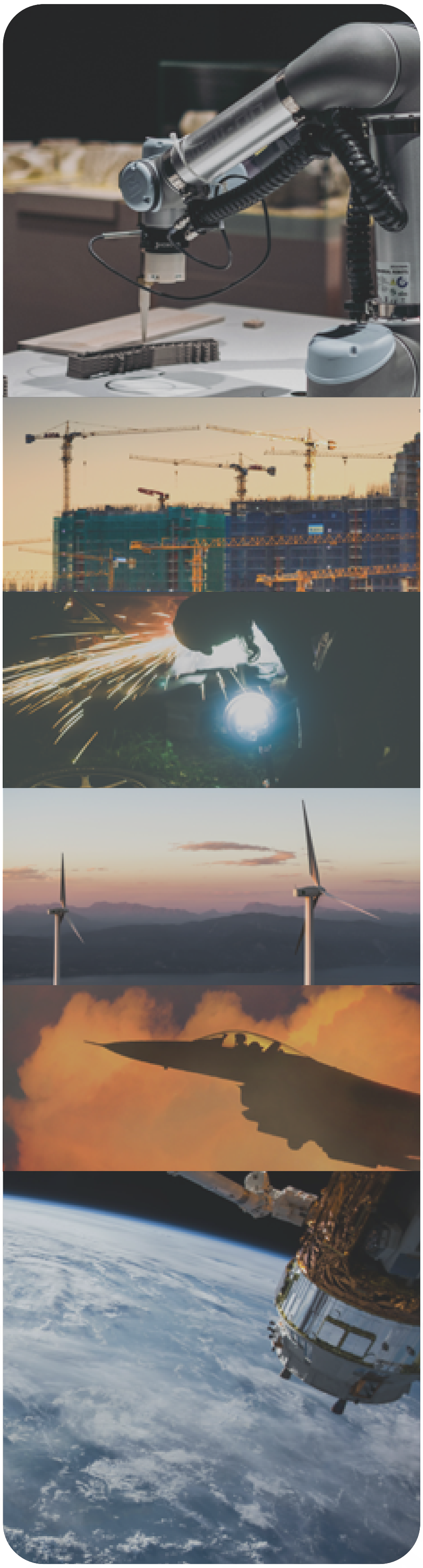
The work packages of this project are to firstly understand and communicate to industry two defined components for coatings, ideally one for corrosion resistance and one in a hydrogen environment, then commission the extreme high-speed laser application (EHLA) and internal bore coating head. Afterwards perform trials and optimise the processing parameters for the two coatings. Then the coatings will be characterised (e.g. optical, SEM, hardness testing) and tested (e.g. corrosion, hydrogen embrittlement), with eventually two demonstration parts being manufactured.

Benefits to Industry

Internal coating by EHLA is proposed in this project as a way to realise the internal coating for applications in corrosion and hydrogen environment due to the benefits of:

- Extreme high speed deposition (10-500X faster compared to conventional internal laser cladding)
- Metallic bonding between substrate the coating
- Low heat input to the substrate and smaller heat affected zone
- Uniform thin coatings (~ 50µm or thicker as required for function)
- High powder efficiency
- Versatile route for exploitation (hard-chrome replacement) and adaptation (robot and repair)
- Multi-material and environmentally-friendly material choices as coatings

If proven successful, the EHLA coating internal bore technology could offer oil and gas industry a game changing solution for their current pipelines and also prepare them for a transition and change into hydrogen transportation and storage in the near future.



Title	Page
Influencing parameters for ultrasonic inspection of austenitic welds Author: *Capucine Carpentier*	41
Annular CO2 corrosion in flexible pipes Author: *John Rothwell*	43
Fatigue performance of large bolts Author: *Carol Johnston*	46
Improving reduced section tensile test specimen geometries Author: *Mike Troughton*	47
Automated process parameter optimisation for robotic arc welding and additive manufacturing Author: *Karan Derekar*	49
Linear friction welding of carbon fibre reinforced plastic Author: *Chris Worrall*	51
Ultrasonic monitoring of electron beam welding Author: *Channa Nageswaran*	52
Multimode virtual source aperture imaging for non-destructive testing Author: *Ewan Hoyle*	53
Hydrogen embrittlement of high strength nickel alloys Author: *Mike Dodge*	55
New tool for joining Ti-6Al-4V by friction stir welding Author: *Jonathan Martin*	57
Fatigue design curves for steel mooring chains in seawater Author: *Yanhui Zhang*	59

CORE RESEARCH PROGRAMME (CRP) INSIGHTS

Influencing parameters for the ultrasonic inspection of austenitic welds
TWI Core Research Programme Project 1153/2021

TWI undertook a Core Research Programme project to generate informative data for the selection of suitable inspection techniques for the testing of austenitic stainless steel welds. This case study presents the scope and activities of the project as well as subsequent follow-on work.

Overview

Austenitic stainless steel (SS), duplex stainless steel (DSS) and nickel alloy (NA) welds and cladding are increasingly being used in the oil and gas, power and petrochemical sectors, and in desalination equipment and wastewater treatment facilities.

Ultrasonic techniques are commonly used for non-destructive testing (NDT) of these materials, as they provide volumetric coverage and are able to interrogate large component thicknesses and complex geometries which preclude radiographic techniques. However, the welds typically display an austenitic structure, which consists of textured large grains, and this results in high ultrasonic scattering associated with mode conversion effects, beam distortion and a variation of ultrasound velocity with direction and position in the weld. Therefore, extensive parametric analysis is required to identify best practice inspection methods for such materials and welds.

It is known that welding procedures, geometry and position are known to have a strong influence on the inspection capabilities of ultrasonic methods. Quantifying the influence of these parameters on the performance of the ultrasound gives an advantage to inspection engineers and asset managers, in terms of selecting suitable inspection techniques and anticipating inspection performance more efficiently. It also reduces the requirement for representative demonstration mock-ups.

Objectives

- Ascertain the relationship between materials and welding parameters, and ultrasonic inspection capabilities and performance
- Establish optimum and best-practice ultrasonic inspection techniques using specimens

Solution

Eighteen representative calibration and welded specimens were fabricated with a variety of differences in material (316L, 304L), welding process (MMA, NGT) and position, namely vertical upwards (PA), downhand (PF) and vertical/horizontal (PC). Defects were introduced within the weld, representing foreseeable defects that could occur during fabrication.

A methodology was established to allow consistent signal-to-noise (SNR) analysis and ultrasonic beam analysis. Each weld specimen went through an extensive set of experiments, including a through transmission hydrophone setup, which allowed for the mapping of the ultrasonic beam after transmission through the weld. Figure 1 shows the setup used to undertake the fingerprint of the welded specimens. Figure 2 shows an example of the ultrasonic beams recorded after transmission through the weld at different sound frequencies.

The defect specimens were then inspected using phased array ultrasonic testing (PAUT) and total focusing method (TFM) techniques using commercially available equipment. The scans made use of dual matrix array (DMA) PAUT probes. The DMA probes have no roof angle, so beam steering was achieved via delay laws in the passive axis. This provided flexibility for the crossing, i.e. focal, point of the transmit and receive beams. In additional, plane wave imaging (PWI) scans were performed using the 5L64 probe with L-wave transmission.

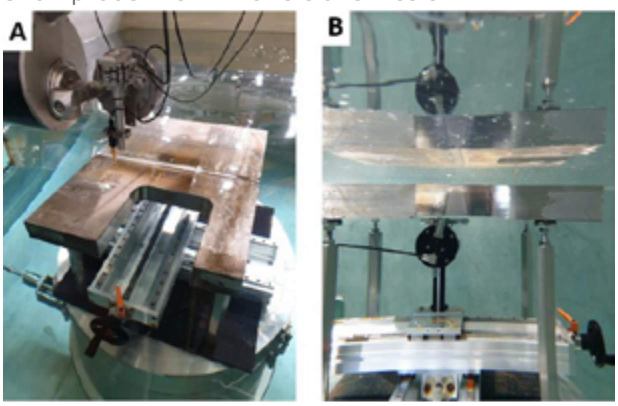


Figure 1. Ultrasonic beam fingerprint experimental setup on a welded component.

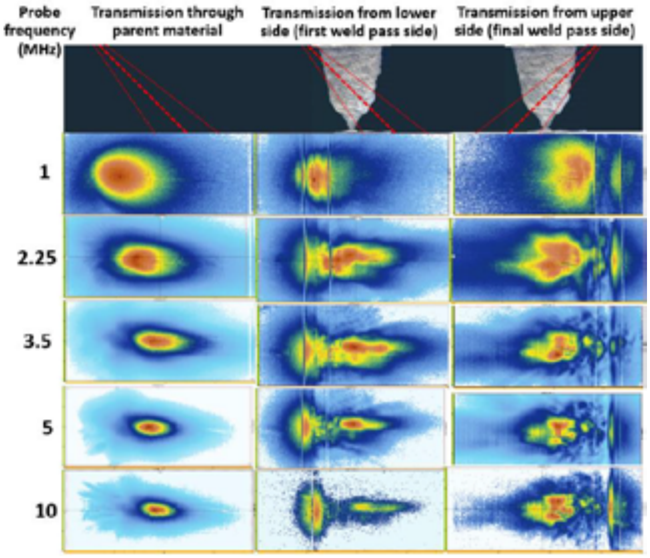


Figure 2. Results of the ultrasonic beam fingerprint.

Conclusion

A methodology was established to characterise the austenitic welds with regards to noise analysis, through transmission beamplot generation and defect inspection in representative specimens. The beamplot analysis showed that ultrasonic beam at the recommended low frequency still presents beam splitting where the major part of the ultrasonic energy propagates downwards towards the weld root. This effect is more pronounced for weld fabricated in vertical upwards (PA) and downhand positions (PF). The noise analysis of the welds showed that the welding position described as vertical/horizontal (PC) presented a significant difference due to the large amount of cross sectional asymmetry in the grain structure. Taking into account the difference in terms of efficient SNR and sizing accuracy between frequencies ranking from 2MHz to 5MHz, it is recommended that different inspection techniques are used for comprehensive detection and sizing capabilities.

This project was funded by TWI's Core Research Programme.

Annular CO_2 corrosion in flexible pipes
TWI Core Research Project 1151/2021 Overview

Although not usually severe, CO_2 corrosion of annular elements has previously been reported (Taylor et al., 2002; Wood, 2017). Furthermore, unusual instances of cracking in CO_2 rich environments in the Brazilian pre-pre-salt have been reported (De Motte et al., 2022). The environmental conditions of the annulus are not straightforward to predict or measure due to the confinement of the wires and the supply of corrosive components via permeation from the bore (see Figure 1). Temperature, partial pressure of acid gases and the degree of occlusion all influence the corrosion rate.

A study was undertaken at TWI in order to determine the annular pH and corrosion rates to flexible pipe environments. Confined conditions approaching those in the annulus of a flexible pipe were created using CO_2 partial pressures at the extreme end of those expected in service. A high strength steel wire grade (>1000MPa Yield) commonly used in flexible pipes was tested.

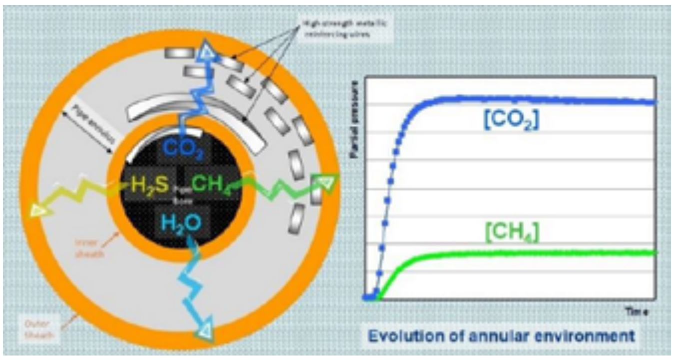


Figure 1. Evolution of annular environment through permeation.

Objectives

- Develop capability for simulating flexible pipe annular environments relevant to service conditions
- Determine the effects of temperature and CO_2 partial pressure on the pH and corrosion rate, relevant to flexible pipe annular environments

Approach

A specialised test facility was commissioned with appropriate instrumentation (see Figure 2). Three autoclaves were operated in parallel at different temperatures, to allow data for three different temperatures to be collected simultaneously. The occlusion ratio (V/A) of the aqueous environment, gas flow rate and partial pressures were defined and continuously monitored.

Figure 2. Laboratory for simulated annulus testing.

- The following variables were explored within the experiments: temperature 30-60°C; partial pressure 1-40 barg; confinement ratio 0.3-1ml/cm^2; duration 58-124 days
- A 3.5wt% NaCl solution and volumetric CO_2 flow rate controlled at 0.001ml/min/cm^2, mimicking permeation flux, was maintained
- In situ pH and dissolved iron [Fe^{2+}] measurements were monitored, and values were compared with commercial water chemistry model predictions
- Test specimens were subject to visual inspection, metallography and scanning electron microscopy
- Corrosion rates were calculated from weight loss measurements
- Profilometry was carried out in order to assess the extent of localised corrosion

Results – pH and dissolved Fe

The long term nature of environmental evolution under nominally constant conditions was reflected in the results (see Figure 3). The pH was seen to stabilise after approximately 30 days, whereas the iron concentrations that developed to peak values within the first few days continued to reduce beyond the 30 day mark. Indeed, the effect of temperature and pressure was more pronounced in the absolute Fe concentrations than for the pH values, although trends between them were similar. Water chemistry models agreed well with the pH measurements when the actual Fe^{2+} concentrations were inputted.

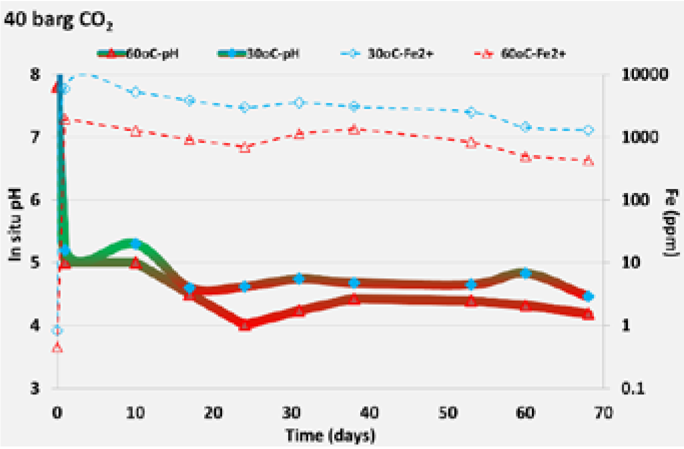


Figure 3. Solution pH and Fe concentration over time.

Over the range investigated, increasing the CO_2 partial pressure increased [Fe^{2+}] and reduced the pH (see Figure 4). The effect of temperature on pH was not consistent at all pressures but overall, an increase in temperature related to a reduced pH. The effect of temperature was more evident in the [Fe^{2+}], with higher concentrations at lower temperatures.

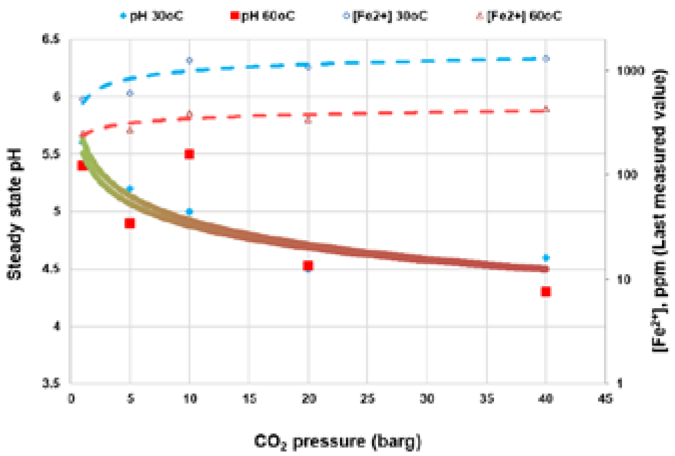


Figure 4. Effect of CO_2 pressure on pH and [Fe^{2+}].

For a given test temperature and CO_2 partial pressure, the pH increased with the concentration of dissolved iron concentration. The test solution remained supersaturated with iron throughout the duration of the experiments. The variation of [Fe2+] could be visualised in the aliquots removed (see Figure 5).

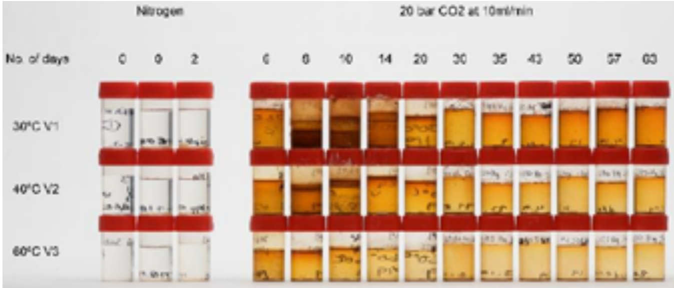


Figure 5. Visual indication of [Fe^{2+}] seen in aliquots extracted over the test duration.

The dissolved iron concentration is associated with the CO_2 corrosion mechanism of steel (Nešić, 2007, Nyborg, 2002). Dissolution of CO_2 acidifies the solution and accelerates the anodic dissolution of steel. The solubility of CO_2 increases with pressure, explaining the more rapid acidification of solution and dissolution of Fe at 40barg CO_2 partial pressure. However, the pH values appeared to substantially converge towards the end of the tests, whereas differences in dissolved iron concentration vs. temperature persisted. The stabilisation in pH values for all test temperatures at 40barg CO_2 and 20barg CO_2 over the long term can be attributed to the stability, structure and thickness of the scales formed.

Results – corrosion rate

It was shown that the corrosion rate decreased as CO_2 pressure and temperature increased (see Figure 6). This is in keeping with trends reported for carbon steels at partial pressures between 15-80barg CO_2, 50-65°C (Choi, 2011; Bai, 2018). However, in contrast to these studies, where corrosion rates were reported to vary between 1 and 20mm/year, the annular corrosion rates in the present study were found to be an order of magnitude lower, at circa 0.1mm/year. The low corrosion rates are associated with the V/A, i.e., the degree of occlusion of the annulus and the supersaturated conditions.

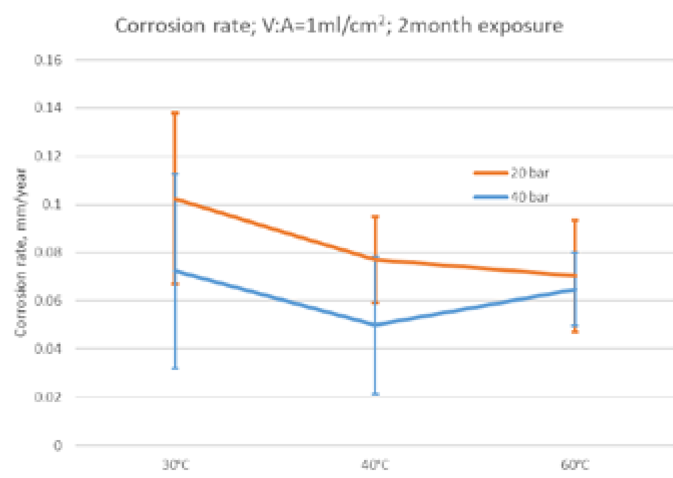


Figure 6. Corrosion rates calculated from mass loss.

Results – corrosion product

Low corrosion rates were associated with protective iron carbonate scale formed on the surface of the test specimens. At 60°C, the scale was thickest. Low V/A ratios, and higher partial pressures both seemed to promote scale (Mitzithra, 2020). At 30°C, more through thickness discontinuities were observed, and these may be implicated in the slightly higher corrosion rates observed. Formation of scales at such low temperatures are not often observed in more open systems, and may be somewhat related to the fluid flow, and increased solubility of siderite at lower temperatures (Anderko, 2000).

Outlook

This project has demonstrated that corrosion in confined annular environments is relatively reduced compared to those in more open systems. Although effects of temperature and pressure were evident, they are relatively inconsequential on an engineering level. However, disruption of the protective scale through upset conditions and fatigue warrants further investigation.

The [Fe^{2+}] and pH were shown to vary significantly over time and this could have a consequence for cracking mechanisms. In particular, the reduction of these values are below those reported in some other short term studies. This highlights a potential issue, for example on the prediction of sulphide stress cracking (SSC) in mild sour annular environments, as it is dependent on both the H_2S partial pressure and the pH.

The CO_2 stress corrosion cracking cited in the literature remains a concern and should be studied further. However, incidences of this issue in the field seem to be rare and no incidents of cracking were identified in this study.

Acknowledgements

We would like to thank Petrobras for their guidance and support of the work, and the TWI laboratory technicians and engineers involved in carrying out this study.

For a list of references, please email crp@twi.co.uk.

This project was funded by TWI's Core Research Programme.

Fatigue performance of large bolts TWI Core Research Project 1155/2021

TWI undertook a Core Research Programme project to determine the fatigue performance of large bolts in both air and seawater environments.

Overview

The fatigue strength of bolts is important to structures that experience cyclic loading. The offshore wind industry, in particular, uses bolted flanged connections in offshore wind turbine structures. One of the fundamental aspects which controls the fatigue strength of the connection is the fatigue strength of the bolts themselves, which was the focus of this project.

Objectives

- Review the literature in order to document the background to the recommendations in existing fatigue design standards relating to bolts and bolted connections
- Carry out tests to determine the fatigue performance of large bolts in air and in corrosive seawater environments in order to check whether the current recommendations and thickness correction for threaded fasteners apply to large, galvanised bolts

Approach

Tests were performed both in air and in an artificial seawater spray environment.

The bolts tested were fabricated by three manufacturers, with different thread manufacturing routes.

Fatigue tests were carried out with a high mean stress of 60 or 70% of the specified minimum yield strength of the bolt.

Results

As expected, the bolts tended to fail on the loaded flank of the first engaged thread (see Figure 1.). Galvanised bolts whose threads had been manufactured by rolling had a lower fatigue performance than uncoated bolts with the same thread manufacturing route. The fatigue performance of galvanised bolts in artificial seawater spray was below their performance in air, but the galvanised coating offered some protection against the corrosive effect of seawater spray, because the fatigue life was only a factor of 1.8 lower than in the in-air performance.

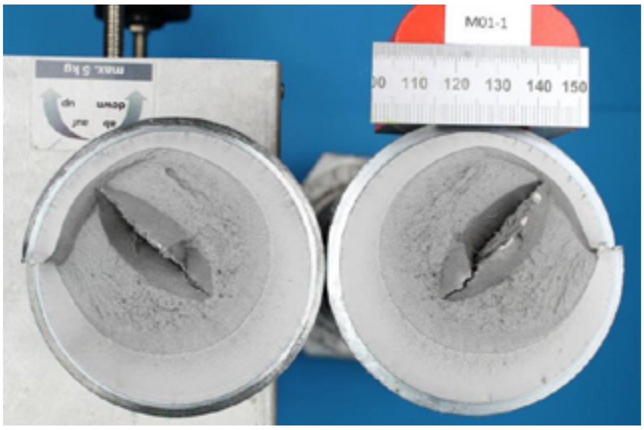


Figure 1. Fracture faces of a cracked M72 bolt.

Conclusions

Users of M72 galvanised bolts can have confidence that the thickness correction in the BS 7608 and DNVGL RP C203 fatigue design guidance documents is applicable when considering the fatigue performance of large bolts. However, the thickness correction recommended in Eurocode 3 and DNVGL ST 0126 over predicts fatigue life, based on the results in this test programme.

The thickness corrected DNVGL RP C203 Class G, or the thickness corrected BS 7608 Class X-20%, design curves are most suitable for describing the fatigue performance of galvanised bolts in air, but the equivalent curves in seawater with cathodic protection (CP) would predict lower fatigue lives than were obtained from the galvanised bolts tested in this programme.

The limited number of test results obtained in this test programme suggest that it would be reasonable to reduce the fatigue life of the in-air DNVGL Class G or BS 7608 Class X–20 % design curves by a factor of two, to calculate the expected fatigue life of galvanised bolts subjected to a seawater spray environment, provided that the galvanised coating remains intact.

This project was funded by TWI's Core Research Programme.

Improvement of the reduced section tensile test specimen geometry for assessing the integrity of butt fusion welds in polyethylene pipes

TWI Core Research Programme Project 1154/2021

Overview

Previous Core Research Programme projects have shown that a tensile test using a reduced section specimen (Figure 1) is the most discriminating mechanical test for assessing the short-term integrity of butt fusion (BF) welds in high density polyethylene (HDPE) pipes. This type of test is specified in a number of standards, including EN 12814-7, relating to the qualification of BF welding procedures and welding operators for HDPE pipes. Most of these standards specify that the fracture surfaces of the tested specimen should be examined and categorised as being either ductile (large-scale deformation of material at the weld interface) or brittle (little or no large-scale deformation of material at the weld interface). However, previous Core Research Programme projects have also shown that the most discriminating test parameter is not the failure mode, which is subjective, but the energy to break the specimen, which is quantifiable.

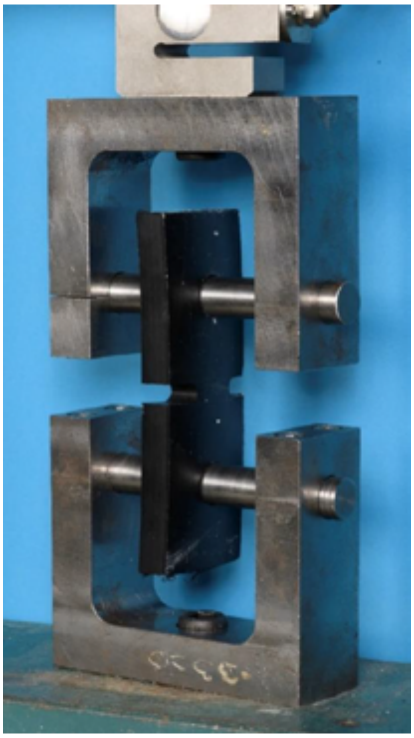


Figure 1. Photograph of a tensile test on a reduced section specimens according to EN 12814-7.

The energy to break the specimen is dependent on its wall thickness; as the thickness of the specimen increases, greater directional stresses (stress triaxiality) are generated, which decrease the ductility of the sample, even for the parent pipe. For this reason, the specimen geometry that is specified for joints in thin walled pipe will not be as discriminating for joints in thick walled pipe, because both good and poor quality joints will fail in a brittle or mixed manner.

Objectives

- Use design of experiments (DoE) and finite element analysis (FEA) to predict the optimal reduced section specimen geometries, in order to generate ductile failures in both parent pipe and good quality BF joints, and minimise the elongation in the loading holes during the test, for all pipe wall thicknesses, and verify these geometries experimentally
- Determine the effect of specimen thickness, on the value of energy to break per unit cross-sectional area (CSA), using the above modified specimen geometries

Approach

In order to improve the geometry of the reduced section tensile test specimen defined in EN 12814-7, this project used two different approaches.

Firstly, tensile tests were carried out on specimens cut from unwelded sheets of HDPE, where the specimen geometry parameters were varied based on a DoE approach. Secondly, the stress field in the specimen was modelled during the tensile test using FEA for different geometry parameters (Figure 2).

To verify the improvement brought about by the DoE and FEA results, tensile specimens with the original geometry, and with the modified geometries, were machined from both BF joints in HDPE pipes of different diameters and wall thicknesses, and from the pipes themselves, and tensile tested to compare their tensile properties and fracture modes.

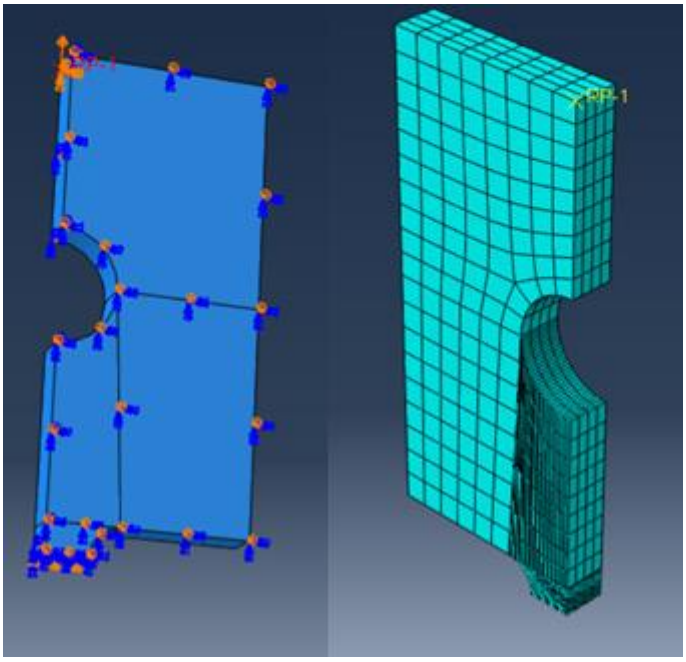


Figure 2. FEA boundary conditions and meshing size used to determine the effect of width of the waisted section, and loading hole diameter, on the elongation in the loading holes.

Results

The results of the DoE and FEA studies predicted three modified specimen geometries, depending on their thickness (Table 1).

Table 1. Dimensions (in mm) for the modified geometry of the reduced section tensile test specimen

Geometry parameter	Wall thickness, mm		
	(a_n<20)	(20≤ a_n<25)	(25≤ a_n<30)
Width of waisted section	15	25	30
Radius of waisted section	10	10	10
Diameter of loading hole	20	25	30
Distance between loading holes	100	105	110
Minimum width of specimen	70	80	80
Minimum length of specimen	190	200	210

By using the modified geometry, the average values of energy to break per unit CSA of specimens from the parent pipe significantly improved for all pipe sizes studied (140mm SDR11 to 630mm SDR11), which verified the DoE and FEA results.

For BF joints with a pipe wall thickness greater than 20mm, the modified specimen geometry significantly increased the ductility and energy to break per unit cross-sectional area compared to the specimen geometry specified in EN 12814-7 (Figure 3).

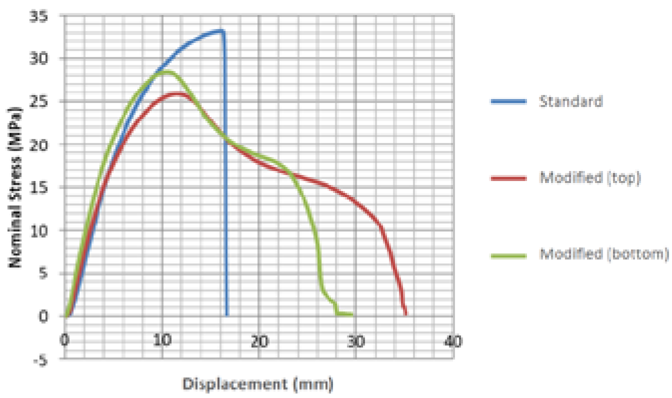


Figure 3. Examples of nominal stress vs displacement curves for the standard specimen geometry (EN 12814-7), and the modified specimen geometries for BF joints in 500mm SDR11 HDPE pipes (full thickness specimen cut in half to produce two specimens).

Although the modified geometry for specimens from BF joints with wall thicknesses below 20mm did not improve the ductility, it significantly reduced the elongation in the loading holes and therefore resulted in a more representative value of energy to break per unit CSA without the need for an extensometer.

Conclusions

DoE and FEA have been used to determine the effect of the reduced section tensile test specimen geometry on the energy to break the specimen and elongation in the loading holes.

This work has resulted in proposed new specimen geometries and a recommendation that the maximum thickness of a specimen should be 30mm. For pipe wall thicknesses greater than 30mm, the specimens should be cut equally into two or more layers such that the maximum thickness of any specimen is 30mm.

The results of tensile tests on the proposed modified specimen geometries, machined from good quality BF joints in HDPE pipes with different outside diameters and wall thicknesses, have shown that the failure is always ductile for all thicknesses.

This project was funded by TWI's Core Research Programme.

CORE RESEARCH PROGRAMME (CRP) INSIGHTS

Automated process parameter optimisation for robotic arc welding and additive manufacturing
TWI Core Research Project 34246/2020

Overview

Multi-axis industrial robots are widely implemented in arc welding production, providing the benefits of increased productivity and improved quality in sectors such as aerospace, rail, power generation and oil & gas structures. When developing the method of manufacturing for a new product, the majority of time is often spent on the determination and development of welding parameters. Identification of the correct parameters is mainly based on trial-and-error experiments incorporating the welding engineers' knowledge and experience, which does not differ from the development of a manual welding process. This could undermine the technical and economic advantages of robotic processes.

This case study reports on minimising the efforts towards parameter development using a numerical modelling approach that is integrated with the robot controller and vision system.

Objectives

- Create and implement numerical models for process parameter development and its integration with robotic metal inert gas (MIG)/metal active gas (MAG) welding.
- Develop and integrate an automated process monitoring system (laser scanning) with the robotic welding process.
- Demonstrate the integrated concept combining the numerical modelling and process monitoring units with the arc welding robot, to contribute to the further development of intelligent automation for arc welding.

Introduction

Industry often requires frequent design changes as part of product development with a corresponding need for requalification of welding procedures for each new design. In this case, the weld qualification process can become time consuming and require significant materials when robotic operation is involved. Frequently, the robotic welding trial process takes longer and costs more than manual welding, owing to the effort spent on robot data analysis, equipment re-programming and revised equipment setup.

To address some of these industrial challenges, a project concept was developed to control weld parameters in real time using a feedback loop system, combining a numerical model and weld monitoring system. Validated numerical finite element (FE) and computational fluid dynamics (CFD) models were applied to map welding parameters and weld beads using the produced weld database. An automated laser based monitoring system was developed to monitor and provide feedback to the control loop.

In this project, the developed modules were tested and validated. The concept can be adapted by other robotic welding and material processing processes. The proposed concept represented an important part of intelligent automation for welding and additive manufacturing.

Approach

Initially, trials were carried out using MAG welding to generate data in the form of temperature variation during welding and weld shape geometry as a function of different welding parameters. This data formed the input for numerical modelling. After obtaining temperature dependent material properties from the literature, two-dimensional, multi-block, structured, quadrilateral mesh was produced for CFD analysis. Wire feed rate, torch travel speed, welding current and voltage were considered variables.

After calibration of the model, weld pool dynamics were assessed for liquid and solid fractions with respect to time (Figure 1). Also, the model was compared with weld macros (Figure 2).

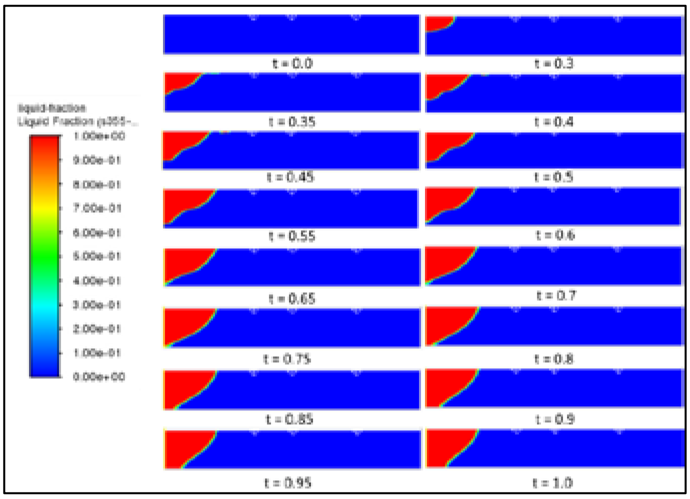


Figure 1 Contour plot of liquid fraction at different times during the welding process.

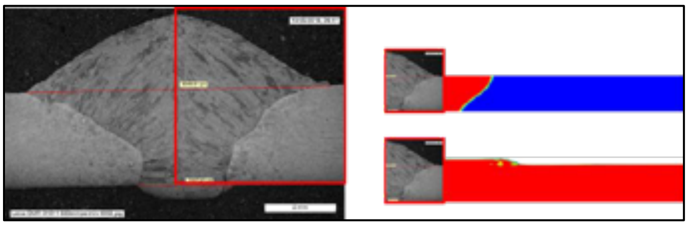


Figure 2 Comparison of modelling results with experimental macrographs.

A laser based camera was used as a monitoring system to gather bead shape information. A representative weld bead shape recorded using the monitoring system is shown in Figure 3 while the recorded data compared with the macro is shown in Figure 4.

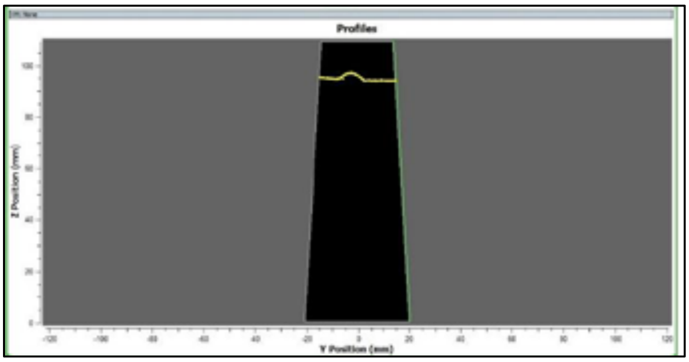


Figure 3 Recorded weld bead dimensions as seen on screen using iCube Servo robot software.

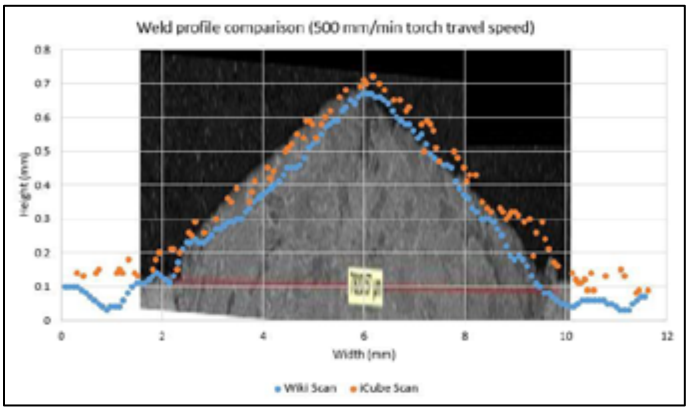


Figure 4 Comparison of monitoring results with experimental macrographs.

Conclusion

- The concept of utilising numerical modelling to enable automatic parameter development and refinement for robotic arc welding process was found feasible. The finite element (FE) and computation fluid dynamics (CFD) based numerical modelling that was calibrated using the data collected from representative welding and monitoring trials showed effective prediction of the impact of welding parameters on the formation of the weld.

- The numerical models developed by the project, which included bespoke heat transfer conditions, was found to be more representative to the real-case scenario, compared with a conventional modelling approach. The conventional approach to apply local temperature-dependent thermal boundaries, were initially applied but found ineffective. To reflect this, the model was modified by removing the bottom layer of gas underneath the workpiece and a CFD based melting model was included. The approach demonstrated effective prediction of weld bead profiles, despite the emerging challenges related to coherently match volume fraction, temperature and liquid fraction results.

- The WiKi scanner and i-Cube camera used as monitoring systems were found to provide reliable outcomes for weld bead shape and size. The data could easily be compared with the outputs of the numerical model. This provided confidence in the integration of the numerical modelling with monitoring systems and weld parameter optimisation.

This project was funded by TWI's Core Research Programme.

Linear friction welding of carbon fibre reinforced plastic TWI Core Research Project 1123/2020

For the purpose of this project, continuous fibre carbon reinforced PEEK (Polyetheretherketone) thermoplastic composite (CFRTPC) was joined using linear friction welding (LFW). Thanks to a PEEK sacrificial interlayer, the strength of the joints produced matched, without any surface pre-treatment, the typical strength of an adhesively bonded joint.

Overview

The rising production rates of the aerospace industry are most likely to be met using thermoplastic composites which, unlike thermoset composites, do not suffer from long cure schedules. Thermoplastic composites can also be joined by thermal welding processes.

LFW is a rapidly developing, solid-phase metals joining process. It is a key technology for critical aero-engine components and is now being qualified for use on aero structures. LFW would typically degrade continuous fibres at the weld interface during welding (Taylor and Jones, 1989) and its application to continuous CFRTPCs has not been achieved.

Adhesively bonded carbon/PEEK laminates have demonstrated joint strengths of up to 28MPa but only after the application of appropriate surface treatment.

Objectives

- Demonstrate welding CFRTPC by LFW
- Mitigate fibre degradation during LFW by adding an unreinforced PEEK interlayer
- Evaluate the strength the CFRTPC joint made on LFW equipment designed for welding metallic parts
- Achieve a minimum joint strength of 25MPa without any surface pre-treatment.

Solution

Adding an unreinforced PEEK interlayer at the weld location was found to be critical in increasing join strength from 17MPa (Taylor and Jones, 1989).

Linear friction welding of pure (unreinforced) PEEK material was first trialled to establish suitable welding parameters.

Then a CFRTPC laminate was manufactured to suit these parameters and a small series of three joints was produced. Figure 1 shows a fully bonded interlayer.

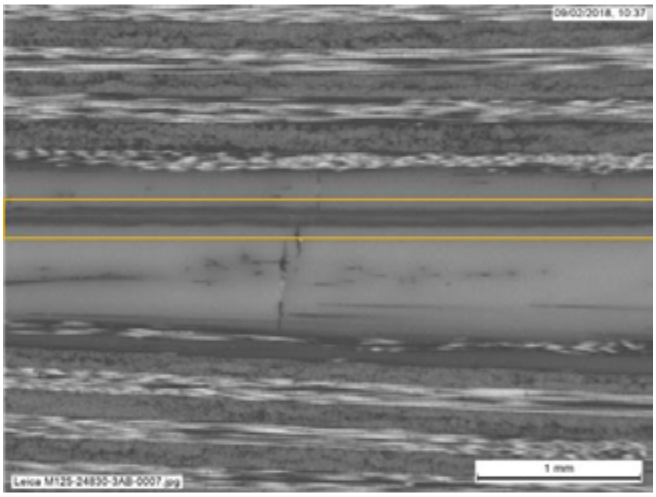


Figure 1. Sacrificial PEEK interlayer between two carbon/PEEK laminates. Yellow lines denote weld location.

Conclusion

The most successful parameters for the CFRTPC joint were 50Hz, ±1.0mm, 40MPa. The PEEK interlayer showed adequate heat generation with non-degraded polymer forged out of the joint. Visual assessment from PEEK welding suggests that applying LFW to CFRTPCs using current metal welding equipment at TWI has the potential to effectively produce welded joints. The welded coupons achieved an apparent lap shear strength of 25.4MPa without any surface preparation.

This project was funded by TWI's Core Research Programme.

Ultrasonic monitoring of electron beam welding
TWI Core Research Project 1134/2020

TWI undertook a Core Research Programme project to create an online monitoring tool for electron beam welding (EBW). This case study presents the scope and activities of the project as well as subsequent follow-on work.

Overview

The EBW process is currently being extended to enable the rapid welding of thick-walled components, as well as being developed for single pass application in the nuclear and the renewables sectors. It is usually performed inside large vacuum chambers, which is not ideal for many industries because of the costs of running large vacuum chambers, hence there is ongoing research and development (R&D) into reduced pressure electron beam welding (RPEBW) systems. A key part of enabling rapid production is the online monitoring of the welding to detect the emergence of any flaws which may be related to welding process parameters, such that immediate feedback loops can correct the parameters for optimum product quality.

Objectives

- Investigate the possibility of using ultrasonic testing (UT) techniques to monitor the emergence of potential flaws in thick-section joints being created using RPEBW systems
- Design a prototype UT system for real-time monitoring of RPEBW in process conditions

Solution

A review of potential UT techniques was undertaken including: time-of-flight diffraction (TOFD); full matrix capture/total focussing method (FMC/TFM); electro-magnetic acoustic transducer (EMAT); and PAUT. The last was chosen because (1) no magnetism, which is not agreeable to EBW, is involved, (2) the data volume is manageable in comparison to FMC/TFM, and (3) it provided options to correct for any image distortions.

The first task was to simulate the transient temperature profiles in the component during a welding event. This was done using finite element modelling. Ultrasonic simulation of the beam propagation in the component, when the metal temperature was ambient and when it was elevated, was utilised to establish the level of any distortion in the imaging, and compared with the experiment. Based on this, a prototype system was designed (see Figure 1), which has since been used in a project for EBW monitoring and is currently being considered for arc welding monitoring.

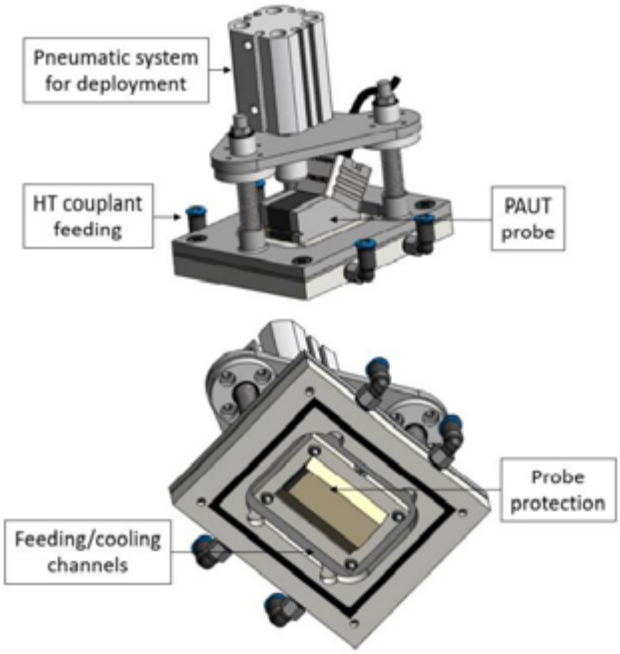


Figure 1. Prototype designed for EBW monitoring tool.

Conclusion

On completion, the project demonstrated that it is possible to undertake online monitoring of EBW, as the temperature levels it requires, using PAUT. Follow-on work then verified the efficacy of the approach for industrial use.

This project was funded by TWI's Core Research Programme.

Multimode virtual source aperture imaging for non-destructive testing
TWI Core Research Project 1148/2020

Overview

Full Matrix Capture (FMC) is an emerging technology in ultrasonic inspection for non-destructive testing (NDT). The ability to generate fully focused images at a practicable frame rate improves inspections by simplifying the setup and flaw recognition for the user. Virtual source aperture (VSA) is a supplementary technique being developed at TWI to improve imaging rates, by combining phased array-like transmission with FMC reception to improve the A-scan signal to noise ratio (SNR) and reduce the number of transmissions required.

Analysing the mode converted signals in VSA data has the potential to reveal extra information about the inspected component that was ultrasonically invisible previously.

This case study reports on the outcome of an investigation carried out deploying VSA imaging for NDT.

Objectives

- Develop a VSA multi-mode imaging algorithm
- Find a computationally efficient approach to solving Fermat's principle of least time

Introduction

There exist several forms in which acoustic energy may travel through a component. The two main modes considered in application for NDT are longitudinal
(particle oscillation in the direction of propagation) and transverse (particle oscillation perpendicular to the direction of propagation). Sound may convert propagation modes and refract when hitting a reflective surface. These mode-converted signals are present in collected data, but are often ignored in favour of the stronger single mode signals.

However, in some cases it may be beneficial to analyse the mode-converted signals. Consider Figure 1 which depicts sound paths for a multimode (Figure 1a) and a single mode (Figure 1b) inspection. The multimode sound path is more likely to return to the transducer to be detected, whereas the single mode is less likely, due to the difference in nature of the refraction angles for single mode and multimode flight paths.

It is necessary for the VSA algorithm to be able to calculate the correct path that sound has taken between any given two points. This is often difficult when the sound has traversed a refractive boundary, which is the case when sound has mode-converted (multimode sound paths). Single mode sound paths are often easier to calculate, due to the symmetry between incident and reflected angles.

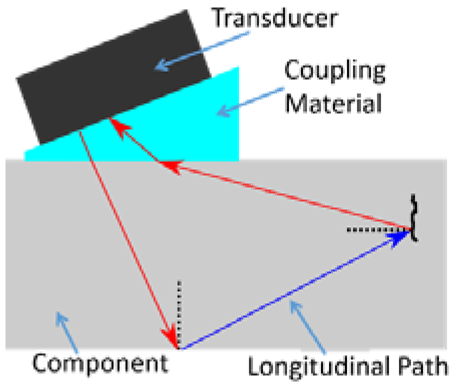


Figure 1a Depiction of sound paths for multimode.

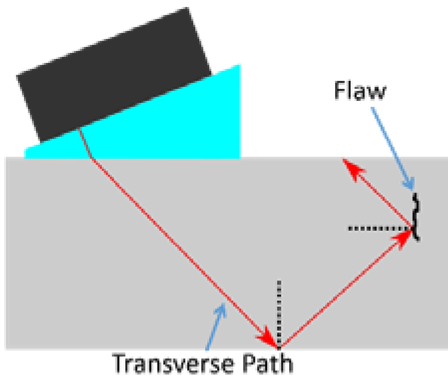


Figure 1b Depiction of sound paths for single mode inspection.

When calculating the path of sound that has experienced refraction, Fermat's principle of least time is often used to find the correct path (the correct path is the path that takes the least amount of time for sound to travel between the source and point of interest). This usually involves a computationally time consuming process, whereby the refractive boundary is traversed. The time of flight is calculated over a range of points, before settling on the least time. This method can be acceptable for a single refractive boundary e.g. between coupling material and the inspected component, but is usually too slow when accounting for multiple refractive boundaries, as occurs With multimode paths.

Approach

The goal was for a time efficient method of solving Fermat's principle for multiple refractive boundaries. In developing a suitable algorithm, first the time of flight equation used for the iterative approach was differentiated with respect to the position on the surface in order to find the gradient. The sign of the result could be used to find the direction of the minimum, relative to any given position on the boundary. Incorporating this information into the iterative approach allows the least time approach to be determined more efficiently, and thereby reduces the processing time.

The same approach can be expanded and used for multiple refractive boundaries, non-flat surfaces and 2D surfaces (where it cannot be assumed that the sound is contained in a single plane).

Conclusion

Compared with other iterative approaches, the new approach to solving Fermat's principle of least time has reduced the path calculation time by a factor of two. This is significant for increasing the frame rate for inspections where the surface geometry relative to the transducer is constantly changing (e.g. in immersion inspection).

The developed VSA multimode algorithm was a success, as it could be used to analyse more of the information contained within the ultrasonic data. The effect of this can be seen in Figure 2. Here, real VSA data was collected using a sample containing a surface breaking flaw. The data was reprocessed using a single mode algorithm (figure 2a) and a multimode inspection (figure 2b). It can be seen that the base of the flaw can only be distinguished using the multimode algorithm. This is significant as the additional information provided by the multimode algorithm could be used for improving the characterisation of the flaw and sizing accuracy.

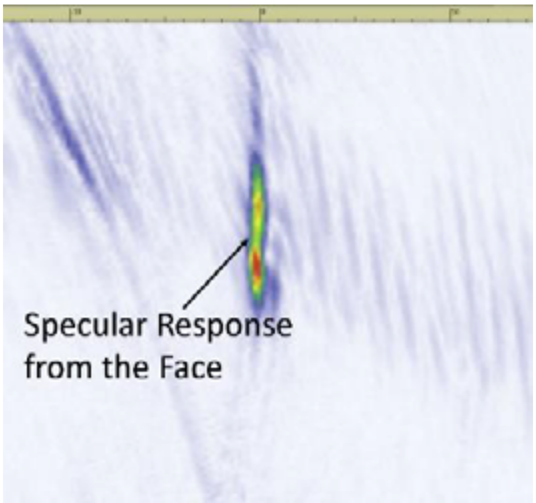


Figure 2a VSA image of a surface breaking flaw using Self-tandem using single mode. Here only the lower part of the flaw can be detected.

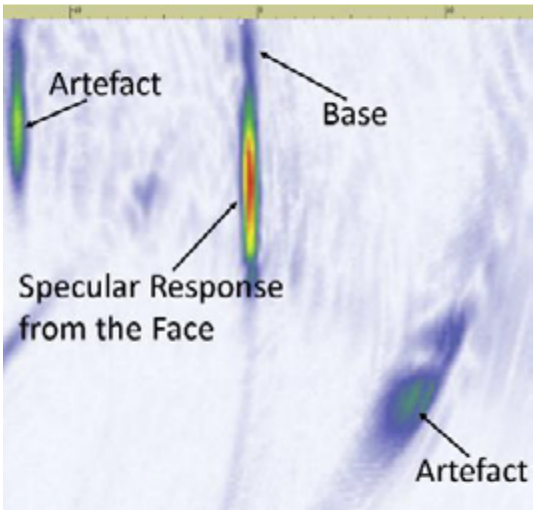


Figure 2a VSA image of a surface breaking flaw using the self-tandem multimode method. Here the base of the flaw can be distinguished.

Please visit TWI's software website for more information on TWI Crystal in relation to FMC and VSA inspection.

This project was funded by TWI's Core Research Programme.

Hydrogen embrittlement of high strength precipitation hardenable nickel alloys
TWI Core Research Project 1128/2020

Precipitation hardenable (PH) nickel alloys are often used in subsea applications where environmentally-assisted cracking is a potential risk. In this project a review of hydrogen embrittlement of PH nickel alloys was undertaken, followed by environmental tensile testing and characterisation, to better understand this mechanism of failure.

Overview

The high strength and corrosion resistance of nickel-chromium-iron alloys, such as Alloys 718 (UNS N07718), 945 (UNS N09945) and 945X (UNS N09946), make them particularly good candidates for use in demanding environments in the upstream oil and gas industry. These materials generally perform well where resistance to sulphide stress cracking, chloride stress corrosion cracking, and hydrogen embrittlement is required. However, environmentally-assisted failures can still occur.

It is generally accepted that for hydrogen cracks to initiate, threshold conditions of stress, susceptible microstructure and hydrogen concentration must be exceeded. Logically, adequate control of any one of these variables would prevent failure altogether. Of course this is not always practicable in the field, and a simpler approach is often to understand how these variables interact, such that the risk of failure can be managed.

The effects of stress, hydrogen concentration and microstructure have been explored in isolation by a number of authors, however, there does not appear to be a unified source of information on the interaction between each variable. In this project, the effect of microstructure was explored by heat treating Alloys 718, 945 and 945X to standard and non-standard conditions. Tensile specimens were slow-strain-rate-tested in air and under cathodic protection (CP) to explore sensitivity to hydrogen embrittlement. Finally, the effect of a severe stress concentration, in the form of a sharp notch, was used to determine whether there was an enhanced susceptibility to hydrogen embrittlement, due to the presence of local stress raisers. The results were compared with tests undertaken by other authors under various hydrogen-charging conditions.

Objective

To evaluate the influence of stress concentration and microstructure on susceptibility of precipitation hardenable nickel alloys to hydrogen embrittlement.

Approach

Unnotched and acutely notched circular cross-section tensile specimens were tested in air and under hydrogen-charging conditions in a solution of 3.5% sodium chloride with CP, to simulate subsea service. After testing, the fracture surfaces were examined at high magnification to determine the fracture morphology at various radial positions.

The materials were also characterised using a combination of metallography, hardness testing, and light and scanning electron microscopy.

Results

Testing of the unnotched specimens under CP did not result in a significant reduction in proof strength. However, there was a clear relationship between increasing material strength, as measured in air, and reduced ultimate tensile strength (UTS) and elongation, when tested under CP.

The materials revealed an increased notch sensitivity, when tested in the presence of hydrogen, particularly for the higher strength materials, such as Alloy 945X (UNS N09946). Notch sensitivity in hydrogen was manifested mainly by reduced UTS. The increased notch UTS sensitivity in hydrogen is attributed to the interplay between strain localisation within the notch, and the propensity for hydrogen to diffuse towards highly strained and plastically deformed regions. It would appear as though the onset of plasticity was the point of divergence in material properties, and that the materials behaved similarly in equivalent tests in air within the elastic regime.

Figure 1 shows the fracture morphology of the hydrogen-charged specimens consisted of a ring of brittle faceted fracture which corresponded to the area into which hydrogen had diffused during pre-charging and testing. Towards the centre of the specimen, the fracture morphology became increasingly ductile.

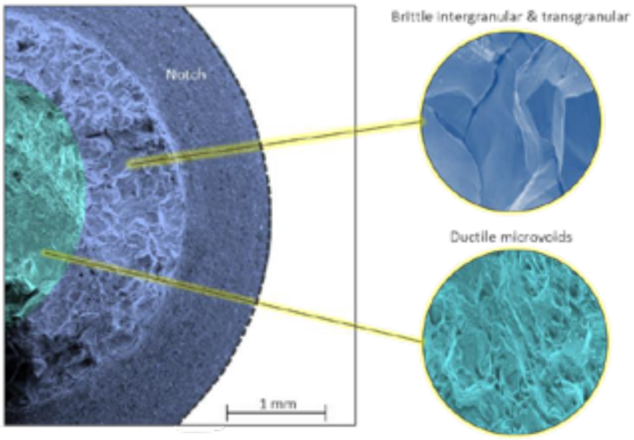


Figure 1. Fracture surface from a notched tensile specimen after slow strain rate testing (SSRT), tested under CP. A ring of brittle intergranular and transgranular fracture is shown around the circumference near the root of the notch.

High magnification inspection of the embrittled portions of the fracture surface revealed the 'brittle' intragranular facets to be populated by slip band traces, the intersections of which were shown to be nucleation sites for micro- and nano-voids. At high strains, it is anticipated these voids will coalesce, resulting in hydrogen crack propagation. Most importantly, these results show that hydrogen embrittlement of these alloys, whilst macroscopically brittle, is fundamentally a high strain and dislocation activated plastic process.

Outlook

This project has shown that the susceptibility of precipitation hardenable nickel alloys to hydrogen embrittlement is governed by microstructure, strength, and the presence and geometry of stress raisers. However, it is understood that materials used in this project are sensitive to the test variables, such as strain rate, pre-charging duration, etc. It is also apparent that the tensile SSRT method cannot quantify the point of crack initiation, or easily distinguish between crack initiation and propagation. These are two fundamental aspects of environmental cracking that need to be better understood. In other words, environmental tensile SSRT, as conventionally carried out and without quantified acceptance criteria, is useful only for basic screening or ranking.

Appropriate guidance should be sought before applying these methods during design, fabrication and service to ensure that components are fit-for-service. Where possible, quantitative methods should be explored, allowing crack initiation to be captured and its significance to the environmental performance of these materials to be determined. These aspects are currently being studied in follow-on programmes at TWI.

Acknowledgements

We would like to thank Special Metals and Titanium Engineers Ltd. for their in-kind contributions to the project. Gisle Rorvik from Equinor is thanked for his assistance in mentoring the project.

This project was funded by TWI's Core Research Programme.

Development and assessment of a new single-use tool for joining Ti-6Al-4V by friction stir welding
TWI Core Research Project 1140/2020

Overview

Friction stir welding (FSW) is now a well-established process for joining light alloys. The relatively low temperature (~500°C) required to soften and plasticise aluminium alloys allows the use of steel based FSW tools, a material which is readily available, low-cost and has a good welding life.

However, tool materials and designs for welding higher temperature alloys such as titanium present a significant challenge, because not only must they be able to withstand high welding forces and torque levels, they must also operate at high temperatures of typically 1000-1200°C. Refractory metals, such as tungsten and molybdenum, are the current preferred materials, but there is only very limited use reported by industry. These have historically provided a FSW tool with properties capable of making welds, however, the cost of the material, producing the tool features and the weld life put a very large burden on the commercial viability of FSW in all but very high value applications. Therefore, a lower cost tooling system could make FSW more financially accessible to a wide range of industries.

Objective

To develop and assess a low-cost, single-use, tooling system based on silicon nitride for welding high strength titanium alloys, particularly focusing on Ti-6Al-4V.

Approach

Following discussions with ceramic suppliers it was identified that the significant cost elements in ceramic FSW tools were the bulk volume of ceramic and the finish grinding of the tool profile post firing. To reduce bulk volume, a ceramic insert mounted in a reusable metallic holder was considered the best option. To eliminate the final grinding operation, the insert would be machined in the green state and then fired. The insert geometry adopted incorporated a tapered body for accurate location and flats for providing a drive feature. The insert had a 3mm probe length. A tool holder was designed to support and transmit the torque to the insert, as shown in Figure 1.

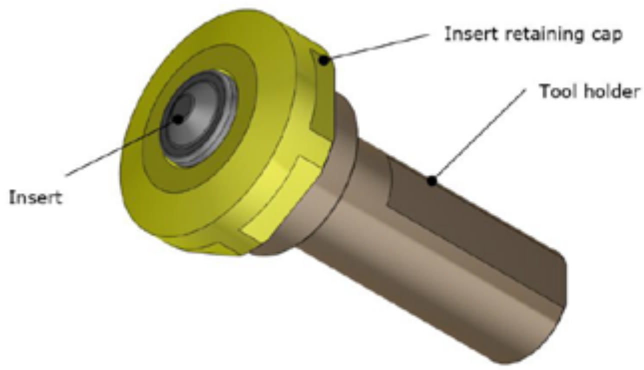


Figure 1. Model of insert and tooling system

A weld procedure was developed for welding Ti-6Al-4V; ceramic inserts from two different suppliers were assessed making bead on plate (BoP) welds. The assessment consisted of visually inspecting the inserts then measuring their geometry using an Alicona Infinite Focus, non-contact profilometer. A two metre long BoP weld was then made, sectioned, and assessed visually by macrograph inspection and transverse tensile testing. Finally, the insert geometry was again inspected using an Alicona Infinite Focus non-contact profilometer. The pre- and post geometry inspection enabled an assessment of the amount of insert material lost during welding.

Results

The insert-based tooling system performed well during welding trials, and the insert holder proved reliable, reusable and provided a good accurate location for rotation. The insert wear observed from the first supplier was consistent; importantly, there was very little material lost from the probe tip, which will maintain the weld stir depth to minimise the chance of producing a weld with lack of penetration. The calculated volume loss of material from pre- and post weld scanning was 71.39 and 72.62mm³ for the two inserts assessed, representing 0.11% by volume of the stirred material volume of the 2m long weld.

The inserts supplied by the second supplier were similar to those of the first supplier, however, the wear was much less severe. The calculated volume loss of material from the two inserts assessed was 45.48 and 43.95mm³ respectively; an average 38% lower than the first supplier and represents 0.07% by volume of the stirred material. It should be noted that the welding parameters used to assess the inserts from the two suppliers were slightly different, which may have contributed to the difference in the calculated volume loss. The most significant wear was again seen in the area where the insert initially contacts the plate in the plunge phase, a little off the probe tip and shoulder areas, with less wear from the curved surface of the probe. Distribution of ceramic particles throughout the weld was not assessed. The strength of the welds produced was slightly overmatched to the parent plate and the welds were free from voids.

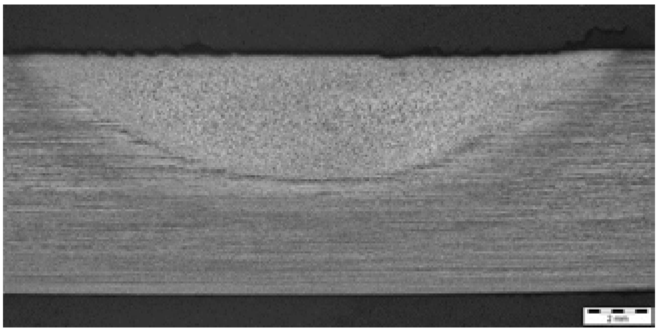


Figure 2. A macrograph of the BOP weld taken from the end of the wear assessment plate.

Conclusion

In developing a tooling system capable of making 3mm deep, 2m long bead-on-plate (BoP) welds, in Ti-6Al-4V using single-use ceramic inserts, TWI has demonstrated the feasibility of using a single-use ceramic insert tooling system for welding high strength titanium alloys. With the inserts costing less than €50, this lower cost tooling system could make FSW more financially accessible to industries other than aerospace, where the product would benefit from the high quality welds produced by friction stir, but could not justify the cost of the current FSW tooling systems.

This project, therefore, represents an important step forward in high temperature FSW with results showing feasibility and practicality of approach. Follow on work will enable further investigation of the loss of material in the weld, leading to a new solution that can be adopted by industry.

This project was funded by TWI's Core Research Programme.

Fatigue design curves for high strength steel mooring chains in seawater
TWI Core Research Project P1135

This case study reports on the outcome of recent fatigue tests on full-scale mooring chains of high steel strength, grade R5 in free corrosion conditions (without protection from corrosion) in seawater.

Overview

Although moorings chains of high strength steel, grade R5 have been used in service in large quantities for many years now, the fatigue design curves are based on the fatigue data of the lower steel grades R3 and R4. Therefore, the fatigue performance of higher strength steel grade R5 chains is not well understood.

Objectives

The objectives of the project were to:

- Conduct fatigue testing in sea water in free corrosion conditions on full-scale mooring chains of R4 and R5 in order to obtain fatigue endurance data
- Evaluate the viability of applying the existing fatigue design curves to a high strength steel, grade R5 mooring chain

Figure 1 Full-scale fatigue test set-up in free corrosion conditions in seawater.

Approach

A test rig, Figure 1 above, was designed and manufactured for testing mooring chain sections of 76mm link in diameter. Six full-scale fatigue tests were conducted: three on high strength steel, grade R4 and three on high strength steel, grade R5. In each test, a chain line of eleven links was loaded under tension into free corrosion conditions in seawater, Figure 1.

When a link failed, it was replaced with a Kenter (temporary) link to enable continuation of the test, until three link failures had been achieved in each test. Magnetic particle inspection (MPI) was carried out to characterise the arising cracking location, crack size and crack growth. Fracture surfaces were examined to reveal any features associated with fatigue crack initiation.

The testing programme generated sixteen link failures: eight from grade R4 and eight from grade R5. Statistical analyses were performed to determine whether the fatigue data associated with R5 was significantly different from that of R4. The fatigue data obtained in this testing programme was also compared with the mean curve for grades R3 and R4, provided by the earlier Noble Denton (ND) Joint Industry Project on fatigue of mooring chains, and the design curves in the API RP 2SK and DNVGL-OS-E301 standards, Figure 2.

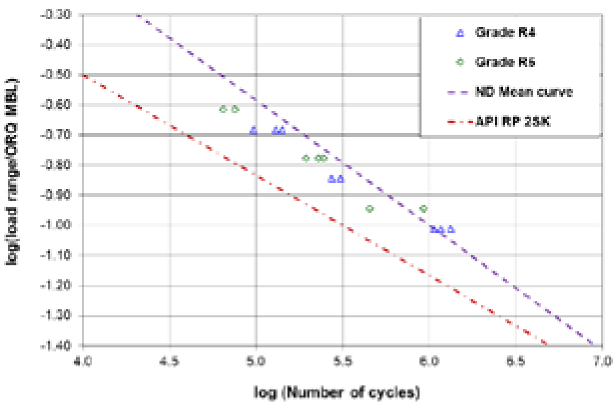


Figure 2 Comparison of fatigue endurance between grades R4 and R5.

Conclusion

Statistical analysis of the fatigue data confirmed that there was no clear effect of free corrosion conditions on performance of the steel grades in seawater, as investigated. The results confirmed that the existing design curves given in standards API RP 2SK and DNVGL-OS-E301 can be applied to studless chain links of high strength steel grade R5.

This project was funded by TWI's Core Research Programme.

Adam Fisher, 2020-2024

Research Title: Atomistic Investigation of Crystal Growth in NiAl Superalloys
Industries: Aerospace, Energy
Industry Supervisor: Dr Huan Wu (TWI)
Academic Supervisor: Dr Peter Brommer and Prof Julie Staunton (University of Warwick)

Muhammad Haris, 2021-2024

Research Title: Corrosion Protection of Dissimilar Materials in Joining Applications
Industries: Automotive, Aerospace, Transport
Industry Supervisor: Sullivan Smith, Dr Ben Robinson, Dr Briony Holmes (TWI Ltd)
Academic Supervisor: Dr Lorna Anguilano, Dr Timothy Minton (Brunel University London)

Man Chi Cheung, 2021-2024

Research Title: Composite-to-Metal Joining for Naval Vessels
Industries: Marine, Transport
Industry Supervisor: Dr Chris Worrall (TWI)
Academic Supervisor: Dr Nenad Djordjevic (Brunel University London)

David Satterlee 2022-2025

Research Title: Extreme High Speed Laser Application Technology (EHLA) of Nickel Superalloys for Coatings and Additive Manufacturing
Industries: Automotive, Aerospace, Oil and Gas, Energy
Industry Supervisor: Josh Barras (TWI)
Academic Supervisor: Dr Stephen Magowan (Sheffield Hallam University)

Alice Appleby, 2022-2025

Research Title: Microstructural Characterisation of Hot Isostatically Pressed ODS 316L Stainless Steel
Industries: Power, Nuclear, Energy
Industry Supervisor: Dr Raja Khan (TWI)
Academic Supervisor: Prof Moataz Attallah (University of Birmingham)

CRP REPORTS LIST
ANNUAL SYMPOSIUM 2023

	Project Title	Date Published	Author
1.	Automated Process Parameter Optimisation for Robotic Arc Welding and Additive Manufacturing 1180/2023	2023	Karan Derekar
2.	Monitoring Corrosion of Marine steels and environments using Acoustic Emission 1179/2023	2023	Rodrigo Rueda
3.	Development of Advanced Material Modelling for Metal Additive Manufacturing 1178/2023	2023	Damaso De Bono
4.	Solidification Cracking Susceptibility of AA6061 and AA2024 Aluminium Alloys during Laser Welding 1177/2023	2023	Yao Ren
5.	Ultimate - Leverage Funding Support 1175/2023	2023	Necdet Capar
6.	Distortion Reduction and Elimination for Additive Manufacturing 1176/2023	2023	Tyler London
7.	Ultrashort Pulsed Laser Surface Modification of Stainless Steel 316L and Titanium Ti-6Al-4V 1174/2023	2023	Andrew Wilson
8.	Industry Guidelines on the Fatigue Performance of Large Bolts 1173/2023	2023	Carol Johnston
9.	Review of the Standard Method for Assessing the Fatigue Life of Bolts in Flanged Connections of Offshore Wind Turbine Structures 1172/2023	2023	Carol Johnston
10.	Integrating Diverse Approaches to the Reliability of Engineering Structures: Applying Probabilistic ECA to Offshore Wind Turbines 1171/2023	2023	Yin Jin Janin
11.	Characterisation of Modified Fibre Based Composites for Enhanced Functionality and Performance (in support of collaborative project MODCOMP)	2023	Chris Graham
12.	Application of BS EN ISO 16827 for Characterisation and Sizing of Discontinuities in Welds Using Advanced Ultrasonic Testing 1169/2023	2023	Kyriakos Flentzeris
13.	Integrating Approaches to Reliability: Refinement of the Fracture Model for Pressure Piping 1167/2023	2023	Yin Jin Janin
14.	Integrating Approaches to Reliability: Performance of Pressure Piping in the as-Welded Condition 1168/2023	2023	Yin Jin Janin
15.	Feasibility of FMC Pitch-Catch for Inspection of Pipeline Girth Welds 1166/2023	2023	Miles Weston
16.	Development of a Mechanised Thermal Cycling Test Facility 1164/2023	2023	Ben Robinson
17.	Corrosion Behaviour of PVD and CVD Wear Resistant Coatings in Synthetic Seawater 1165/2023	2023	Ben Robinson
18.	Cold Spray Deposition of a Powder Produced from a Beta Titanium Alloy 1163/2023	2023	Henry Begg
19.	Quantification of Hydrogen in TSA-Coated API 5L X80 and AISI 4137 Steels Exposed to Seawater 1162/2022	2023	Shiladitya Paul
20.	Technical Literature Review of Telerobotics for Welding 1161/2022	2022	Robert Shaw
21.	Integrity in Aggressive Environments 1159/2022	2022	Kuveshni Govender
22.	The Influence of Stress Concentration and Plastic Strain on the Resistance of Precipitation-Hardened Nickel Alloys to Hydrogen Embrittlement 1160/2022	2022	David Griffiths
23.	Investigating the Influence of Pre-tension on Fatigue Performance of Large Bolts 1158/2022	2022	Carol Johnston
24.	Effect of Insufficient Homogenisation of Pigmented Resin During the Extrusion of Polyethylene Pipes on the Mechanical Performance of Butt Fusion Joints 1157/2022	2022	Mike Troughton (previously Steve Willis)
25.	Damage Tolerance of Thermal Spray Aluminium (TSA)	2021	Shiladitya Paul
26.	Fatigue Strength of Large Bolts	2021	Carol Johnston
27.	Determination of Waisted Tensile Test Energy-to-Break Factors for Different Polyethylene Pipe Pesins	2021	Mike Troughton
28.	Influencing Parameters for the Ultrasonic Inspection of Austenitic Welds	2021	Channa Nageswaren (previously Jack Lambert)
29.	Annular Corrosion in Flexible Pipes	2021	Maria Eleni Mitzithra

30.	Development of Customisable and Scalable Phased Array Instrument Boards for Intrinsically Safe Environments	2021	Giorgos Asfis
31.	Development of Laminographic Reconstruction Methods for 3D Industrial Inspection	2021	Mark Sutcliffe
32.	Development of Offset X-ray and Panel Shift Computer Tomography Inspection	2020	Alan Clarke
33.	Advanced Virtual Source Aperture Imaging for Non Destructive Testing	2020	Ewan Hoyle
34.	Monitoring of Arc Welding	2020	Robert Shaw
35.	Assessment of HPHT Conditions: Survey of Industry Requirements	2020	David Smyth-Boyle
36.	Developing Gas Plasma as a Universal Dry Pre-treatment for Structural Bonding Applications	2020	Ewan Keller
37.	Signal Processing Techniques for Guided Wave Inspection of Buried Pipelines	2020	Ruth Sanderson
38.	Effect of Welding Parameters on the Integrity and Structure of Butt Fusion Welds in Polyethylene Pipes	2020	Muhammad Shaheer
39.	Assessment of Mechanical Fastening Techniques for Dissimilar Metals Joining in Car Bodies	2020	Sullivan Smith
40.	Welding of Additively Manufactured Materials: Preliminary Assessment	2020	Adrian Addison
41.	Preliminary Mechanical Properties of Thermoplastic Composites Containing Multiple Pierced Perforations	2020	Chris Worrall
42.	Shearography of Wind Turbine Blades	2020	Jianxin Gao
43.	FSW of titanium alloys	2020	Jonathan Martin
44.	Refill Friction Stir Spot Welding Parameter Development for Transport Industry Aluminium Alloys	2020	Anthony McAndrew
45.	Integrating Diverse Approaches to the Reliability of Engineering Structures; Background and Example Calculations	2020	Isabel Hadley
46.	Fatigue Testing of 76mm Diameter Mooring Chain in Seawater	2020	Yan-Hui Zhang
47.	Ultrasonic Monitoring of Electron Beam Welding	2020	Shiva Majidnia
48.	Evaluating Fracture Behaviour of Pipeline Steel in a Sour Environment at Ambient Temperature	2020	Muhammad Ali
49.	The Effects of Welding Conditions and Postweld Heat Treatment on the Corrosion Performance of Friction Stir Welded High Strength Aluminium Alloys	2020	Hua Zhang
50.	Green Laser Cutting of Fibre Reinforced Polymers	2020	Yao Ren
51.	Validation of BS 7910:2013 and R6 Fracture Assessment Procedures: Summary Report, Including Treatment of Plastic Collapse, Weld Strength Mismatch and Probabilistic Data	2020	Isabel Hadley
52.	Friction Stir Spot Welding: Process Capability Study	2020	Kathryn Beamish
53.	Treatment of Residual Stresses in Engineering Critical Assessment Considering Elastic Follow-Up	2020	Guiyi Wu
54.	The Effect of Microstructure on Resistance to Hydrogen Embrittlement of Notched Corrosion Resistant Alloys	2020	Michael Dodge
55.	The Prediction of External Corrosion in Pipelines from Survey Data	2020	Chi Lee
56.	Adhesive-free Bond Strength Test Method for Cold Spray Coatings	2020	Ben Robinson
57.	Linear Friction Welding of Advanced Materials - Carbon Fibre Reinforced Plastic	2020	Bert Flipo
58.	Elucidating the Process of Environmentally-Assisted Cracking in Duplex Stainless Steel Weld Microstructures	2020	Mike Gittos
59.	The Robustness of the Guided Wave Flaw Sizing Technique Pipeline Inspection in the Field	2020	Ruth Sanderson
60.	Improvements to Guided Wave Focusing for Pipeline Inspection in the Field	2020	Jane Allwright
61.	Linear Friction Welding of Advanced Materials – Aluminium Copper Lithium Alloy	2020	Bert Flipo
62.	Comparison of Methods to Determine Tearing Resistance Curves in SENB Specimens	2020	Philippa Moore

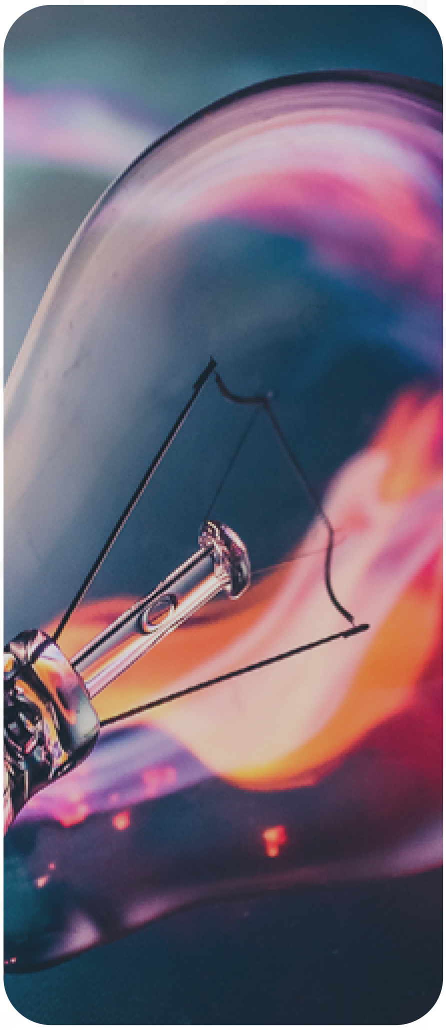
TWI INNOVATION NETWORK

TWI Innovation Network (TWIIN) is an open innovation ecosystem connecting companies and organisations globally for collaboration and engineering technology acceleration. With a particular focus on joint research and development (R&D) through grant funded engineering technologies projects – TWIIN creates opportunities for SMEs, medium sized and larger companies, university institutions, and research and technology organisations (RTOs) – nurturing business growth across the innovation supply chain, with programmes, centres and activities that go deeper than norm.

TWIIN's portfolio of innovation focused activities include:

- The **National Structural Integrity Research Centre** (NSIRC) – post graduate study programmes in an industrial engineering environment
- **Innovation Centres** – joint industry-research partnerships between TWI and academia developing new engineering technologies
- **Technology Acceleration Programmes** (TAPs) – collaborations with SMEs, TWI Industrial Members and TWIIIN Members to move innovative concepts through to commercialisation
- **Private Technology Partnerships** (PTIPs) – long-term relationships with technology organisations to develop novel solutions and address industrial challenges
- **TWI Innovation Network Subscription** – different options designed for companies and organisations looking to build their technology and marketplace ambitions
- **Technology Innovation Management** – opportunities to join like-minded consortia on collaborative projects for grant funding proposals
- **Innovation Consultancy Services** - a more tailored, 1-2-1 approach for accelerating innovation processes, leading to new product, system and service development
- An annual programme of **in-person events and online webinars** – opportunities for project collaboration, partner-matching, networking and gaining new insights

INNOVATION CONSULTANCY SERVICES



Innovation Consultancy Services (ICS) provides tailored innovation tools and solutions for companies / organisations looking to implement new growth and business strategies, helping to create opportunities for technology acceleration, promote products and services, identify new markets through research and networking activities, and more.

The ICS team will work with you to optimise your business, selecting the most appropriate service(s) to meet your objectives. Take a look below at just some of what they can provide.

Innovation Management

- Innovation audits and strategies
- Innovation process development
- Innovation tools
- Risk management

Unlocking Opportunities

- Ideation workshops
- Partner recruitment
- Concept development
- Project management
- Mock reviews of bids

Technology Management

- Technology roadmaps and canvassing
- Technology maturity assessments, foresight and intelligence
- Market analysis

Why our members work with us

Trusted partner

We have over 500 Industrial Member companies already trusting us to provide them with expertise. A full list of Member companies is available on ***our website***.

Expertise and knowledge

All our staff are highly trained and respected experts in their fields. Alongside academic qualifications many of our staff associate with the Institute individually and uphold the standards of qualification required.

Cutting-edge technologies

Over the last 80 years we have brought technologies to the forefront of industry. From the invention of Friction Stir Welding to the acquisition of the UK's first dedicated EHLA system for research, we remain at the front of knowledge development in new fields.

Certified and accredited

We are certified against ISO9001 and ISO14001 in all our own work. We can work to and test against a huge range of ISO and ASTM standards, and our teams contribute to dozens of Standards Committees every year.

Collaboration and funding

We have an excellent track record for winning public funding bids, including Horizon and Innovate UK mechanisms among others. We have dedicated teams working on consortium building and project development, and have won more than £5M of projects in the past 5 years.

All your joining needs

Our knowledge base expands far beyond arc welding into full-service joining process management. We can support the full throughput of work under one roof; from design and adherence to standards, to modelling of the process, process monitoring, and non-destructive inspection of the final part.

Recognised brand

TWI Ltd is recognised internationally as a stamp of high quality training, certification and advice. You will be supported by staff who are valued and respected for their expertise in specialist fields.

Dedicated care teams

We have a dedicated Membership team on hand to support you and ensure you get the most out of your membership without interrupting your technical discussions. Our central project management team can support large programs of work to keep strands on track, and our Library service will source information and documents for you as needed for your research.

TWI Training and Examinations

Flexible Training Solutions

TWI Training and Examination Services
Tel: +44 1223 899500 Email: trainexam@twitraining.com
www.twitraining.com

TWI CORE RESEARCH PROGRAMME

ANNUAL SYMPOSIUM 2023

TWI CRP, Granta Park, Abington, Cambridge CB21 6AL
TWI is the business name of The Welding Institute, a company limited by guarantee.
The Welding Institute - Registered number 405555 England.
TWI - Registered number 3859442 England.

Visit: WWW.TWI-GLOBAL.COM/CRP

Email: CRP@TWI.CO.UK