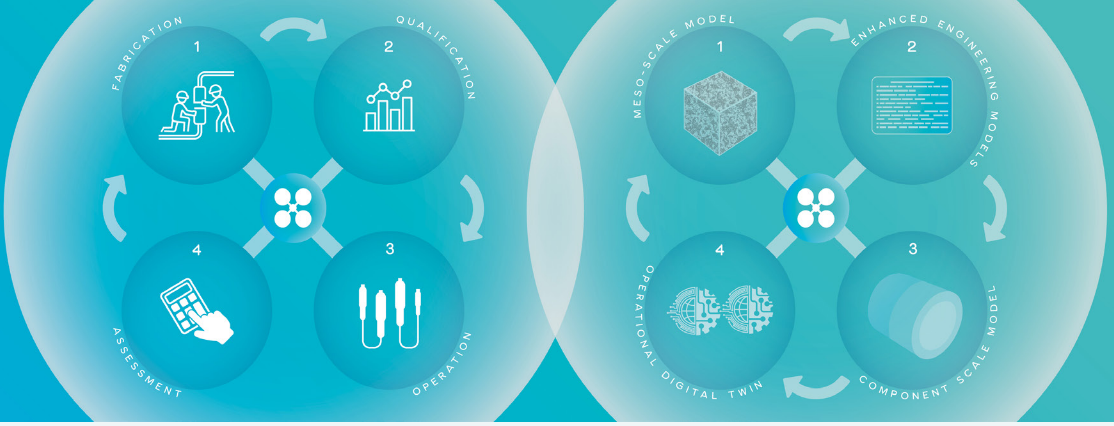

SINDRI: Synergistic utilisation of INformatics and Data centRic Integrity engineering

Business Lead: EDF | University Lead: University of Bristol | Grant reference: EP/V038079/1

SUMMARY

The Synergistic utilisation of INformatics and Data centRic Integrity engineering (SINDRI) Prosperity Partnership is developing digital tools that will revolutionise the nuclear industry's design and in-service assessments of materials and components. These tools will speed up the implementation of innovative designs and transform the way the industry conducts structural performance assessments. SINDRI will use advanced materials predictive models, underwritten by high fidelity experiments, together with model reduction methods, to automate time-consuming, manual processes within a virtual environment.

INTRODUCTION AND BACKGROUND

The nuclear industry faces substantial technical challenges in delivering cost effective technical solutions which will allow it to play a major role in the delivery of a carbon-neutral economy by 2050. The SINDRI project therefore aims to develop open-source, digital tools that will accelerate construction and reduce OPEX in the nuclear industry. By building on existing software, the project aims to eliminate significant time-consuming and cumbersome human interventions enabling high throughput analysis which can accommodate next generation probabilistic analysis.

SINDRI is a collaborative effort between academia and industry and supports several national initiatives such as the Small Modular Reactor Programme and the UKAEA's STEP program. A Prosperity Partnership is the optimal route to achieve the objectives of SINDRI as it brings together key expertise across science and engineering and provides a rapid route for testing and implementation within industry.

KEY TECHNICAL OBJECTIVES

- Quantify the effects of fabrication and in-service environment on materials microstructure and its evolution using high-fidelity experiments.
- Employ and develop microstructurally informed, multi-physics models to simulate fabrication and in-service behaviour of representative alloy systems.
- Implement data-based methods and approaches such as model reduction, data assimilation, and uncertainty quantification to enable modelling activities to cross length scales.
- Provide a controlled and validated toolbox of approaches to the nuclear industry to underpin a robust probabilistic approach distinct from the current, expensive, and conservative deterministic methods.

PROJECT ACHIEVEMENTS: OUTPUTS, OUTCOMES, AND IMPACT

Substantial breakthroughs and advancements have been made in the SINDRI project, 20 months since its launch. With a robust research framework in place, the project has successfully completed key deliverables, actively engaged with stakeholders, and begun pilot testing of technologies within industry. Below are some selected project highlights:

Development of novel, phase field frameworks for predicting solidification microstructures

In order to understand how differing processing parameters lead to different solidification microstructures, a novel multi-component multi-phase field framework has been developed. This framework can be used to simulate the solidification of any alloy, with any number of chemical species, and grains. Furthermore, this framework fully captures all 5 degrees of freedom of the solidifying grains, both rotational and inclination dependent. While this framework is all-encompassing for predicting the solidification microstructures in multi-component alloys, it is computationally expensive due to the number of transport equation partial differential equations that must be solved. Figure 1 shows the mesh invariance of the included 5 degrees of freedom anisotropy in the multi-phase, multi-component implementation.

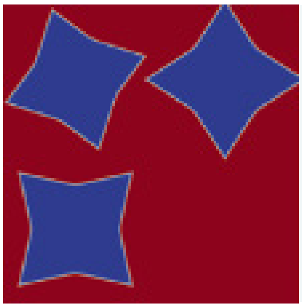

Figure 1 Demonstrating the rotational invariance of the anisotropic multi-component, multi-phase field framework.

To reduce the computational cost, a single-component, multi-phase field framework has also been developed which will allow us to investigate the microstructures formed over larger length scales than the higher fidelity approach, this can be seen in Figure 2. Both of these phase-field frameworks are being used in the SINDRI project as a tool to link processing parameters to the solidification microstructures in the substrate.

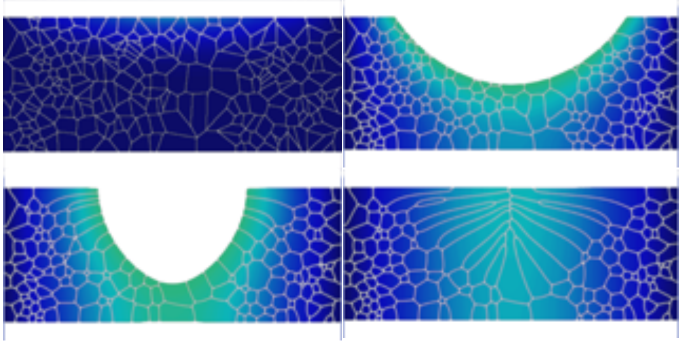

Figure 2 Predicted grain-structures produced from melting and re-solidification using a single-component, isotropic, multi-phase field framework.

Breakthrough in multi-scale modelling framework to improve prediction of key performance parameter with validation through an industrial case study

Significant effort was spent connecting meso-scale modelling to higher length scale modelling suitable for component simulation and their validations. An industrially relevant case study was selected to showcase the multi-scale modelling framework developed in the project, this was Electron Beam welding. The weld microstructure was analysed and characterised using state-of-the-art techniques at national facilities (Diamond Light Source and Henry Royce Institute for Advanced Materials). The microstructure was also simulated using high performance computing and its mechanical response was predicted as shown in Figure 3. This response was exported to the next length scale simulation technique (continuum finite element analysis) suitable for estimating the mechanical behaviour of an industrial component as described in the next section.

Implementation of a multiscale modelling approach for predicting mechanical response of an Electron Beam weld in type 316L stainless steel

The stress-strain mechanical response of an Electron Beam weld in type 316L stainless steel has been modelled successfully. The development of the residual stresses and strains was predicted using an uncoupled thermal-mechanical finite element simulation where a double-ellipsoidal-conical heat power density model was employed, which has been shown to more accurately describe transient temperature fields in Electron Beam welds.

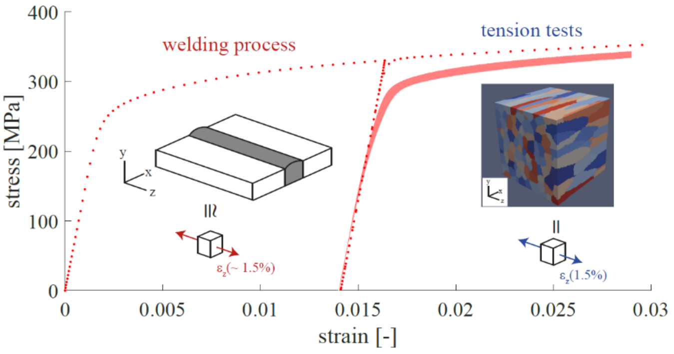

Figure 3 Prediction of weld material properties from parent material. The dotted line shows the simulated material property and the solid line is the mechanical testing of the welded material. The dotted line predicts the behaviour of welded material before welding process which is input into the weld simulation.

In a further refinement, the mesoscale modelling of mechanical response approach described above was applied to the weld microstructure and combined with the process simulation of the welding technique through finite element analysis via an iterative process. Employing this approach, predictions of the residual stresses are refined by the actual weld microstructure and the output demonstrates excellent agreement with experimental measurements.

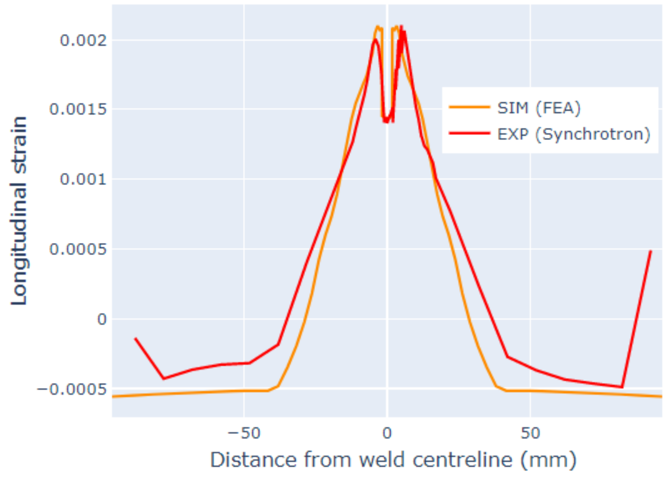

Figure 4 Longitudinal elastic strain versus distance from the weld centre at mid-thickness.

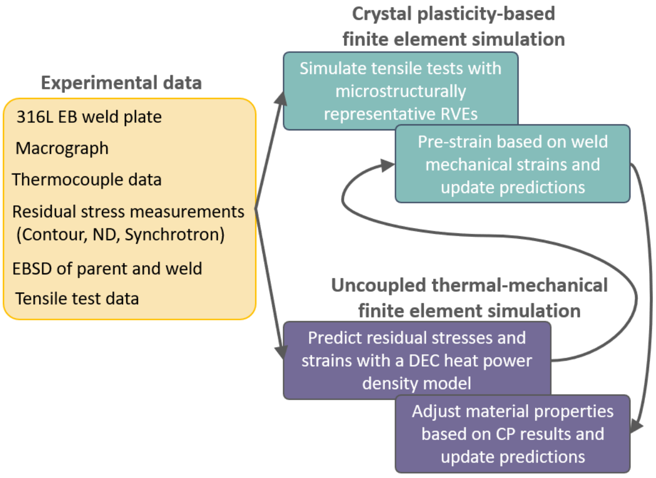

Figure 5 Schematic of modelling approach for weld residual stress simulation.

The longitudinal strains can be seen in Figure 4 in comparison with a synchrotron measurement, where the characteristic 'M' shape at the weld centre is observed. The schematic in Figure 5 demonstrates the modelling workflow.

SINDRI Toolbox evolution and practical implementation of the Weld Workbench

The SINDRI Toolbox, is the digital platform that will facilitate the delivery of the SINDRI objectives. It is a method to encapsulate all of the research-based outputs from the project, in a systematic way that considers the full software lifecycle (Figure 6). This is imperative for adoption of new methodologies in industry where there are stringent quality control standards in place.

Within this toolbox the SINDRI project has seen significant development of the weld workbench, a tool dedicated for weld residual stress modelling, which aims to address issues of model complexity. It is designed to make the setup, running and interpretation of finite element-base models easier, quicker and as pain free as possible. It employs open-source automation of the best-in-class modelling procedures put forward by industry and academia. This will alleviate many of the time-consuming errors and bugs that are prohibitive for producing reliable and repeatable residual stress predictions.

Figure 6 The development stages for the SINDRI Toolbox.

The tool, its concept, and architecture, have been tested by engineering teams within EDF group and has been presented to industrial stakeholders and engineering consultancies in the supply chain who have provided early-stage feedback.

It is anticipated that PhD students, from other project teams, will start to utilise this tool for their research. Moreover, external academics from other universities are keen to access and contribute to this tool through other projects.

The welding workbench is already available as a module within the SINDRI Toolbox and in 2023 the tool will undergo testing and rigorous benchmarking against other commercial tools for weld residual stress modelling. Furthermore, users can look forward to the development of new features, including the ability to account for metallurgical phase transformations in ferritic materials, the ability to use it on pipes and full prediction of 3D residual stresses in single pass welds.

ENGAGEMENT AND DISSEMINATION

The SINDRI team have been presenting their tools and findings and engaging stakeholders at various events and conferences nationally and internationally. Highlights include:

- Application of Data Science and AI in the Nuclear Industry at Data Week 2022 - SINDRI hosted a workshop with presentations from industry stakeholders including The ONR, Rolls Royce, CEA, UKAEA and Jacobs.
- ONR & NNL Expert Panel: Regulation of Artificial Intelligence in Nuclear - Participation by David Knowles (University of Bristol) and Hadiza Mohammed (University of Bristol)
- TU Graz Seggau 2022 Conference (Austria) – Presentation by Alexandre Paget (University of Manchester)
- FFM Matériaux 2022 Conference Lille (France) – Presentation by Alexandre Paget (University of Manchester)
- IOM3 2022 Manufacture & Materials for Fission & Fusion Net-zero – Presentation by Mahmoud Mostafavi (University of Bristol)

STAFF HIGHLIGHTS

Awards

- ImechE Donals Julius Groen Prize (2021) awarded to Dr Thomas Flint, (The University of Manchester): for his paper “Magneto-hydrodynamics of multi-phase flows in heterogeneous systems with large property gradients.
- Metmat Contest of Metallurgy and Materials Photomicrographs (2022) Second place awarded to Dr Julio Spadotto, (The University of Manchester).
- The Nuclear Industry Benevolent Fund Career Development Bursary (2022) Awarded to Dr Maria Yankova, (The University of Manchester).

New Staff and Team Developments

- Dr Julio Spadotto has joined the SINDRI team as a PDRA at the University of Manchester
- Dr Chen Liu has joined the SINDRI team as a PDRA at Imperial College London
- Dr Nicolo Grilli has joined the SINDRI team as a Co-I at The University of Bristol
- Dr Thomas Flint has been promoted within SINDRI from a PDRA to a Co-I
- SINDRI Co-Lead Marc Chevalier has been promoted to Advanced Reactor & Structural Integrity R&D Manager at EDF Group