A thermal-mechanical uncoupled simulation to model the effects of residual stress in a butt-welded Eurofer-97 joints tensile response

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Abstract

Amidst the current global climate emergency, the need to find viable and sustainable sources of energy generation is at an all-time high. However, the current nuclear capability is not sufficient to meet current or future global requirements, showing more research is required if commercial viability is to be achieved [1]. Nuclear Fusion is of much focus owning to its potential for long-term and sustainable energy generation. This involves research into the different components of Nuclear Fusion reactors, including the breeding module and divertor. This is highlighted in the international effort currently being made towards the DEMOnstration power plant (DEMO), which requires interdisciplinary partnership for both research of the many connected systems and governing bodies alike if the goal of the first commercial fusion reactor is to be met [2]. Part of that international effort involves a structural integrity assessment in order to take conceptions through to design and ultimately, operation whilst proving adequate performance and safety.

Research pivotal to the structural integrity assessments is the mechanical performance of the different joining mechanisms found in-vessel, which allow the complex geometries of the breeding module and divertor to be made. Welding is one of the most important joining processes, however this leads to the introduction of residual stress (RS), which can be detrimental to the mechanical performance of many in-vessel components, where Eurofer-97 (E97) is to be the main material for DEMO. RS is well-established to potentially aid in crack growth propagation and reduce the fatigue lifetime of components [3]. RS is then clearly an issue for the service life and the structural integrity assessments of components within Nuclear Fusion reactors.

This research has then the purpose of capturing the residual stress and understanding its effects on the tensile performance for a E97 butt-weld, with the aim of starting to build a framework that can be extended beyond these criteria. The Finite Element Method (FEM) was used to achieve this and is well established in these contexts from previous authors [4-6]. FEM in this context removes the need to perform actual weldments on materials, saving both time and cost. In addition, it removes the need for RS measurement tests, which require in-depth knowledge and careful data analysis, and all have their disadvantages.

FEM has been applied to simulate the residual stress generated in the fusion zone, heat affected zone and base material for a Eurofer-97 similar butt-welded joint. This is an uncoupled simulation consisting of a thermal analysis followed by a tensile mechanical test, using the results from the thermal analysis as input. A non-uniform moving heat source model via Abaqus DFLUX subroutine with element birth and death as a form of material deposition was used, followed by the inclusion of martensitic phase transformation and changes in the materials yield stress due to these transformations via UEXPAN and UHARD respectively.

Results from the thermal simulation are expected to yield an 'M' shaped residual stress profile with respect to distance from weld centre, and the inclusion of phase transformations ensures this curve will be more accurate. When compared to a simulation without the effects of residual stress added, the global effects of the addition of this stress differential and changes in yield stress can be explored, after which the results will be compared to experiment to validate this method of capturing residual stress.

As mentioned, the purpose of this work is to start building a FEM framework for nuclear materials with the aim of extending to more materials, different types of joints and further mechanical tests so FEM can be used as a predictive tool to assist in structural integrity assessments.

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