Residual stress prediction by element birth within a digital twin of a wire arc additive manufacturing cell

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Additive manufacturing is becoming ever more prevalent in high value manufacturing of metal components. One such industry which is looking at highly bespoke, large, low volume metal components is the fusion industry as it moves towards a functional fusion power plant for electricity generation. An example of a relevant component is that of the inner pressure vessel of a stellarator, a type of fusion reactor design. This pressure vessel is a toroidal ring, with cross section on the orders of meters with constantly varying shape and is used to confine the plasma for fusion. For such large scale, thin walled, complex geometry fusion components wire fed arc direct energy deposition (DED), also referred to as wire arc additive manufacturing (WAAM), would appear to be a logical solution for manufacturing.

The WAAM process is based on the use of a welding torch to lay down layers of liquid metal, which then solidify, layer by layer, to produce a 3D component. An example of a scaled down section of a stellarator inner plasma vessel based on the W7-X stellarator design [1] which has been produced by the authors using WAAM is shown in Figure 1. The position of this torch is controlled by robotic arms which can be programmed to create the desired shape on a layer-by-layer basis. The additive manufacturing cell used to manufacture this component is shown in Figure 2a.

Figure 1. Scaled subsection of the stellarator inner vessel manufactured by WAAM.

A digital twin of the additive manufacturing cell has been developed as described by Li *et al* [2]. This digital twin is capable of monitoring the position of the robots in the cell and playing back their movements in a digital environment, Figure 2b. The digital twin also uses a laser scanner attached to a second robotic arm to record the true deposition at intervals throughout the build. This record of the geometry can be stored and rendered in the digital environment.

Due to the high temperature nature of the build and related high temperature gradients, high levels of both distortion and residual stress are likely to occur. Understanding this distortion and residual stress is vital to both the successful finishing steps of the manufacture, as it could result in the part being out of tolerance, and the lifespan or viability of the final product. Reliable modelling and measurement of residual stresses is therefore highly important to the use of techniques such as WAAM in fusion relevant components. Element birth or "Block dump" style modelling of residual stresses is well employed for the prediction of stresses in welding [3] and has also been extended to additive manufacturing techniques such as laser powder bed fusion [4]. This technique has been applied by the authors to the stellarator geometry to model the WAAM manufacturing of the stellarator section. An example temperature prediction for a subsection of the build made with the ABAQUS finite element package is shown in Figure 3.

The nature of additive manufacturing and the presence of the digital twin allows for the geometry of the model to be based of the desired shape to be manufactured, such as that in Figure 3, or in principle the actual manufactured shape, as captured by the laser scanner. The efforts to allow the true manufactured geometry to be used for finite element modelling will be explored along with a comparison to the idealised input geometry, all within the context of the digital twin.

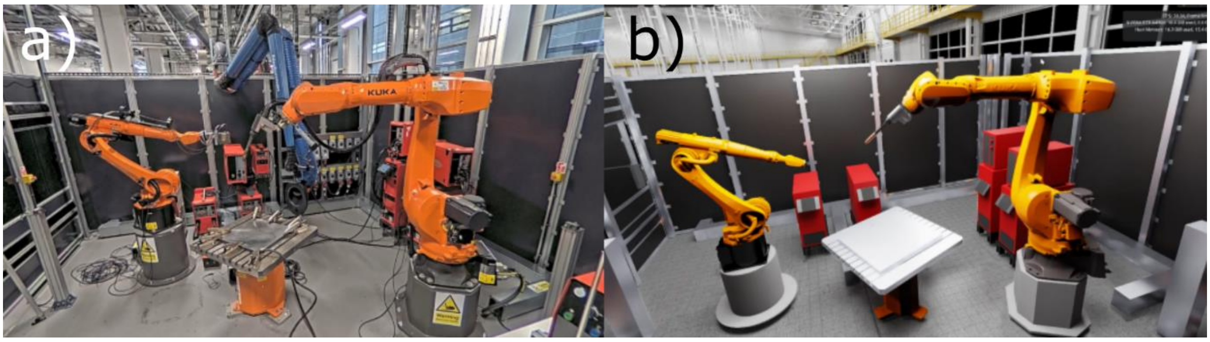

Figure 2. Physical manufacturing cell (a) and digital twin of manufacturing cell (b). Robot fitted with laser scanner (left) and welding torch (right) will manufacture the part on the build plate (centre).

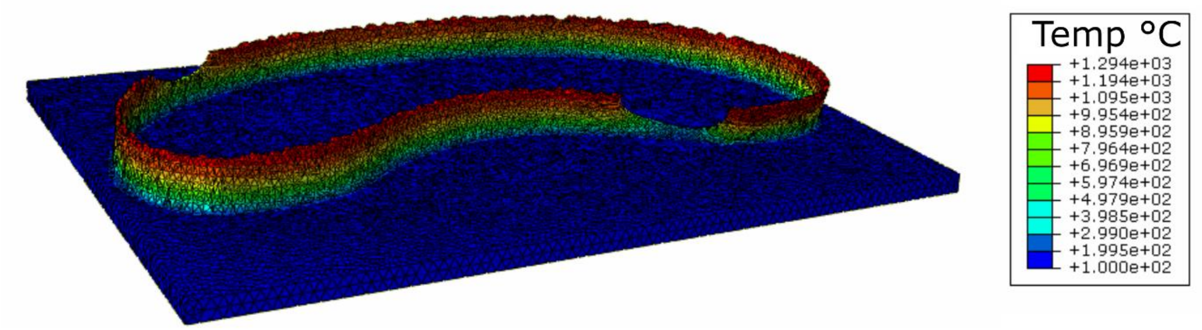

Figure 3. Thermal prediction of temperature in a section of the build after the deposition while cooling.

1. Reich, J., et al., *Manufacture of the vacuum vessels and the ports of Wendelstein 7-X.* Fusion Engineering and Design, 2005. **75-79**: p. 565-569.
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3. Truman, C.E. and M.C. Smith, *The NeT residual stress measurement and modelling round robin on a single weld bead-on-plate specimen.* International Journal of Pressure Vessels and Piping, 2009. **86**(1): p. 1-2.
4. Sandmann, P., et al., *Influence of laser shock peening on the residual stresses in additively manufactured 316L by Laser Powder Bed Fusion: A combined experimental–numerical study.* Additive Manufacturing, 2022. **60**: p. 103204.