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Develop baseline computational model for proactive welding stress management to suppress helium induced cracking during weld repair

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W. Zhang and Z. Feng, ORNL

1. Background and Objectives

There are over 100 nuclear power plants operating in the U.S., which generate approximately 20% of the nation's electricity. These plants range from 15 to 40 years old. Extending the service lives of the current fleet of nuclear power plants beyond 60 years is imperative to allow for the environmentally-sustainable energy infrastructure being developed and matured. Welding repair of irradiated nuclear reactor materials (such as austenitic stainless steels) is especially challenging because of the existence of large amounts of helium in the steel matrix after intense neutron exposure. Under the influence of high temperatures and high tensile stresses during welding, rapid formation and growth of helium bubbles can occur at grain boundaries, resulting in intergranular cracking in the heat-affected zone (HAZ). Over the past decades, a fundamental understanding has been established for the mechanism of stress evolution during welding and the detrimental effects of weld stresses on weld cracking. However, practical methods for weld repair of irradiated materials are still evolving.

This task was to develop the initial baseline version of weld computational model that can be used to determine the optimum welding conditions to manage the weld stresses during welding and suppress helium induced cracking during weld repair of helium containing irradiated materials. This model was to be used for quantitative understanding of the temperature and stress evolution in the weld HAZ. The initial results obtained using the baseline computational model for proactive welding stress management to suppress helium induced cracking during weld repair are reported as follows.

2. Initial results

The weld thermal-stress model takes into account welding parameters, material properties and part geometry to calculate the transient temperature and stress distribution during welding. In our initial development of the model, laser welding processes was selected based on the recommendations of industry collaborators, as the low heat input and other advantages of laser welding process make it mostly suitable for repair welding of irradiated materials.

Figure 1 presents a snapshot of the temperature distribution during weld repair of an AISI 304 stainless steel plate by the laser welding process. The region represented by the 1680 K isotherm (red) corresponds to the molten pool created by the intense heating of a welding laser beam. Outside this weld pool is the weld HAZ, where the temperature is just below the melting temperature. This location is most susceptible to helium induced cracking because of the existence of both high temperature and high tensile stress there. The detailed temperature and stress histories at two monitoring locations in the HAZ are illustrated in Figure 2. As shown in this figure, the transverse stress quickly becomes tensile upon cooling. The tensile stress is more

than 200 MPa as the weld temperature drops to 1000 K. The combination of high tensile stresses and high temperatures is largely responsible for formation of helium-induced cracks during welding.

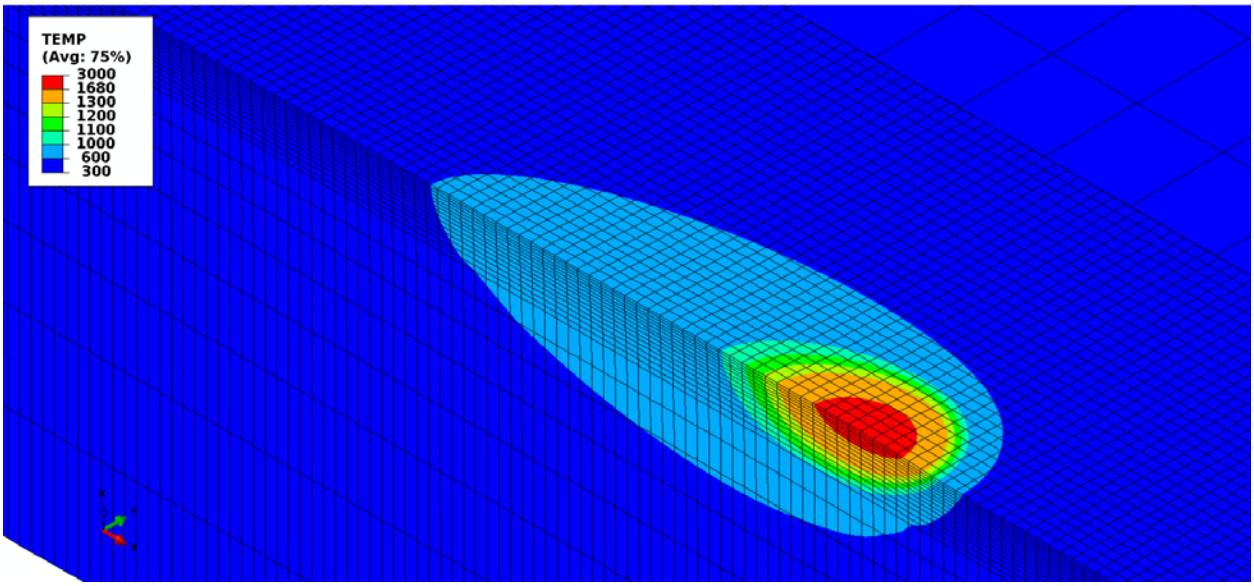

Figure 1. Snapshot of temperature distribution during welding. The temperature is given in Kelvin. Only a half of plate is shown to reveal the temperature distribution on the weld central plane.

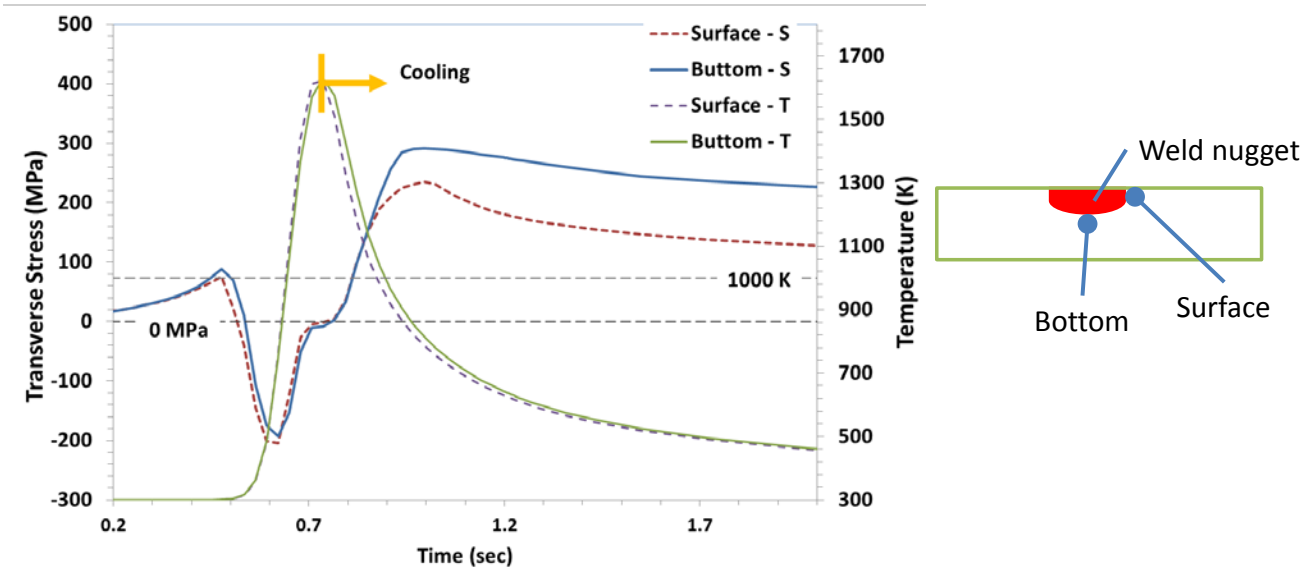

Figure 2. Evolution of transverse stress and temperature during welding at two monitoring locations in the heat-affected zone (HAZ) adjacent to the weld pool.

The baseline computational model was then applied to evaluate different approaches to manage the weld stresses to suppress helium induced cracking during repair. Several promising approaches have been identified. The specifics of the approaches and modeling results are described in a recent ORNL Invention Disclosure [1]. As such, they are omitted in this report.

3. Future work

Leveraging ORNL's previous and ongoing efforts in modeling of helium bubble nucleation and growth kinetics, the baseline computational model will be further developed to calculate the likeness of helium induced cracking under various welding conditions. Such quantitative knowledge is essential for optimizing the effectiveness of stress management approach for crack mitigation during weld repair of irradiated materials. Furthermore, the weld model will be calibrated and validated against the experimental data which are generated in another task of the project.

References

[1] W. Zhang, Z. Feng and E. Willis, In-situ Stress Alteration using Auxiliary Heating during Welding, ORNL Invention Disclosure No. 201102565.