Soak Time, Hours	Dye Penetrant Inspection		Ultrasonic Inspection	
	Weld Toe A	Weld Toe B	Weld Toe A	Weld Toe B
4,274	NRI	NRI	NRI	NRI
7,621	NRI	NRI	NRI	NRI
10,518	75mm intermittent	6mm intermittent	NRI	NRI
13,880	90mm intermittent	18mm intermittent	NRI*	NRI
17,583	89mm intermittent 8mm	54mm intermittent 12 mm intermittent	NRI*	NRI*
27,654	88mm intermittent	45mm	NRI*	NRI*
34,410	90mm intermittent 5mm intermittent	NRI	NRI*	NRI*

NRI = No reportable indications. * = Intermittent indications below the reporting threshold.

stress relaxation following reheat crack initiation has not been modelled in the current analysis. Additionally, the predicted length of the subsurface cracks from the model is less than those recorded from the thermal soak specimen. The source of this difference is considered likely due to creep crack growth during the thermal soak test which is not included as part of the numerical simulation.

The predicted average creep damage in the worst element at one third of weld depth (reaches unity at about 5,000 hours. The creep damage in the worst element near the weld surface, which is at a line about 45° to the weld surface, also reaches unity again at about 5,000 hours. Compared with the DPI inspection results on the surface defect, considering the time it would take for the creep cavities to develop into detectable creep crack, the current reheat crack initiation model is well validated by the thermal soak test results.

SANS VALIDATIONS

SANS Measurements of Creep Cavitation

The development of creep cavitation is a useful indicator of creep damage but is difficult to determine using conventional microscopy as the cavities and carbides are too small. Small angle neutron scattering (SANS), was used to measure the degree of cavitation (6-300 nm diameter in size) in a sample of Weld 3 after the thermal soak test. SEM analysis was also conducted to complement the findings from the SANS experiment (not shown).

For the purpose of the SANS and SEM measurements, three 1mm thick slices, adjacent to each other, were removed parallel to the weld fusion boundary in the HAZ region of specimen Weld 3 at distances of 4.1mm, 5.2mm and 6.3mm from the weld fusion boundary. This was close to the fusion boundary whilst avoiding intersection with the cracked areas of the thermally soaked specimen. The SANS measurements were carried out with the support of Open University, on the SANS2D small-angle scattering instrument at the ISIS Pulsed Neutron Source at the Rutherford Appleton Laboratory.

In order to measure the creep cavities along the crack in specimen Weld 3, sixteen positions at 3mm intervals along the Slice 1 were marked up for the measurements. In addition, two positions were examined away from the crack/weld fusion boundary in Slice 2 and Slice 3, near the middle of the weld and at the root. These positions for Weld 3 are shown in Figure 9.

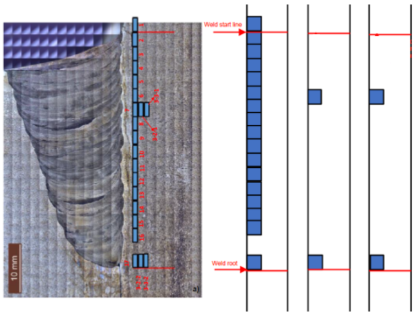


Figure 9: Schematic presentation of the SANS measurement positions in specimen Weld 3 a) top view of the measurement windows, overlaid against the weld macrographs and b) side view of the measurement windows (as in front of the SANS beamline).

Analysis of SANS Data

A fraction volume distribution of cavities may be interpreted as the 'relative' fractional volume distribution due to creep induced cavities alone, by subtracting a far-field measurement that is due to other precipitates, with no cavities present. The far-field measurement was taken from similar measurements in the HAZ of a weld from the mock-up showing particularly low numbers of cavities (Weld 4). By dividing this by the contrast factor for cavities, the 'true' fractional volume distribution of cavities, C(D), can be calculated. The above approach can be used to determine the 'true' fractional volume distribution of cavities, C(D), at each measurement position. The fractional volume distribution of cavities measured by SANS at different positions along Weld 3 Slice 1 (parallel to fusion boundary) is shown in Figure 10.

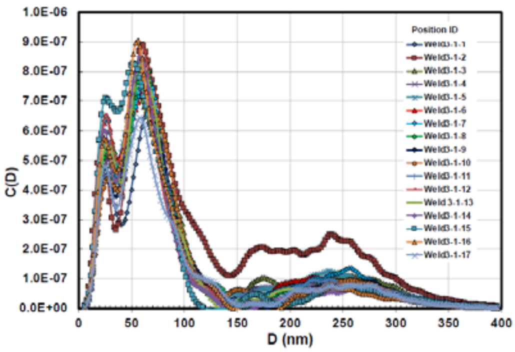


Figure 10: Fractional volume distribution, C(D), of cavities measured by SANS at different positions along slice 1 (parallel to fusion boundary)

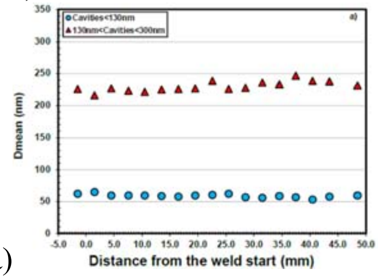
Further, the number density Nd(D) of defects with diameter in the range D to D + δD can be calculated from the relation Nd (D) = C(D)/Vsph(D) where Vsph(D) is the volume of a spherical defect of diameter D (= πD3/6), and Nd(D) is the number density per unit of D3.

From Figure 10 measurements of the measured size distribution exhibits two populations of cavities, a population of smaller cavities under 130 nm in size, and a population of larger cavities 130-300 nm in size. In order to estimate the number density of cavities from the above relation, in a given diameter range in the size distribution, the integral over C(D) in each peak has been determined and divided by the corresponding mean diameter of the peak.

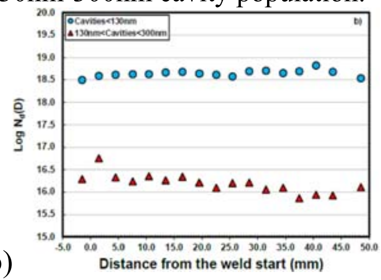
The variation in the mean size and the number density of two populations of cavities, (those less than 130nm and in the range 130nm-300nm) were quantified and are presented in Figure 11a and b respectively for positions along the crack. It is seen that, the smaller sized cavities have a higher number density compared with the larger sized cavities. Also, it is seen that the number density of the larger population of cavities increases approaching the weld toe.

It is hypothesised that the larger SANS cavity population in the range 130nm-300nm may correlate with significant creep damage. Comparison of the FE predicted Weld 3 creep damage along a similar slice to the SANS measurement plane is presented in

Figure **12**. The FE shows the highest damage is predicted in the top half of the weld and less damage near the root, with a similar distribution evident for the 130nm-300nm cavity population.



a)



b)

Figure 11: a) Mean cavity size, Dmean (in nm), and b) number density of cavities, Nd(D) (in m-3), for two populations of cavities as a function of distance from the weld toe along slice 1.

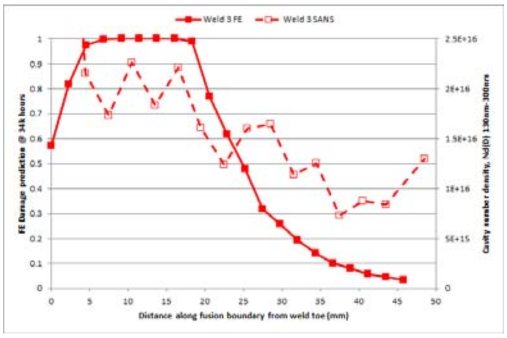


Figure 12: Comparison of FE damage predictions and SANS cavity number density along fusion boundary.

CONCLUSION

The FE predictions of reheat cracking show similar temporal and spatial behaviour to the cracking observed in thermally soaked test specimens. Further, measurements on the thermally soaked specimens indicate a potential correlation of predicted creep damage with measurements of the numbers of cavities made using SANS. This provides some confidence in the techniques used for numerical modelling of reheat cracking, and the potential to quantify creep damage in austenitic material using SANS.