Solid State Phase Transformation and Restraint in Residual Modelling of 100+ Pass Low-Alloy Steel Welds

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Motivation

The long-term safety cases for extension of current nuclear power stations and of future reactors requires strong understanding of the residual stress state brought about during fabrication of thick-section (>100mm) high-integrity welded components relating to the pressure vessels. Welding of thick sections also requires significant restraint, which has the potential to alter the final residual stress distribution and distortion is prevents during manufacture. When low-alloy steels are used, as they regularly are, the solid-state phase transformations which occurs during welding will also alter the final residual stress state. This evolution is exacerbated in multi pass welds. In this work the importance of considering these effects when undertaking residual stress prediction by finite element model is explored through application to a 130 mm thick multi-pass (100+) weld created for the NUMMAN [1] project (Fig 1.).

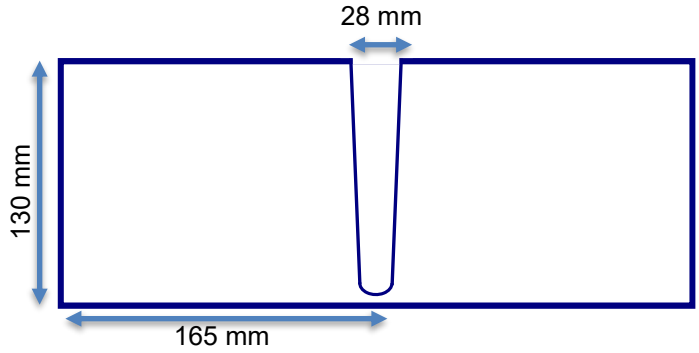

Fig 1. Layup for the 130 mm NUMMAN weld, plates have full depth of 575 mm.

Modelling Approach

Sub-continuum microstructural changes in both parent materials and weld fillers for multi-pass welds (100+ passes) were modelled along with the microstructural evolution, the thermal history and the predicted residual stress state. This investigation was conducted using ABAQUS and a series of user sub routines [2] developed at the University of Manchester. Themo couple data and cross-sectional micrographs of the weld fusion boundaries from the NUMMAN weld was used to calibrate the heat source using FEAT-WMT. This heat source was applied to a 2D slice at the centre of the weld's longitudinal direction, activating each pass at times dictated by the experimental interpass times. First a thermal meterlergical solution was conducted, which was used to inform a mechanical simulation to predict the residual stress.

To investigate the effect of different levels of restraint three versions of the model were conducted representing no restraint (only free body motion prevented), over restraint (the entire base of the layup being prevented from vertical motion) and an attempt to represent the experimental restraint rig (which was substantial [1]) using connector spring elements.

Post Weld Microstructure

Fig 2. shows the model 2D weld cross section and the presence of phase predicted at the end of the weld using the thermal metolergical model. There is a significant of bainite in the final weld, with the second most represented phase being ferrite. This is in contrast to the weld while solid but at temperature which is dominated by austenite. The heat effected zones of each pass leave a distinctive pattern as sections are remelted and others are not with subsequent passes. The presence of these phases results in varying material properties and generate misfits within the structure which will locally effect the residual stress state predicated.

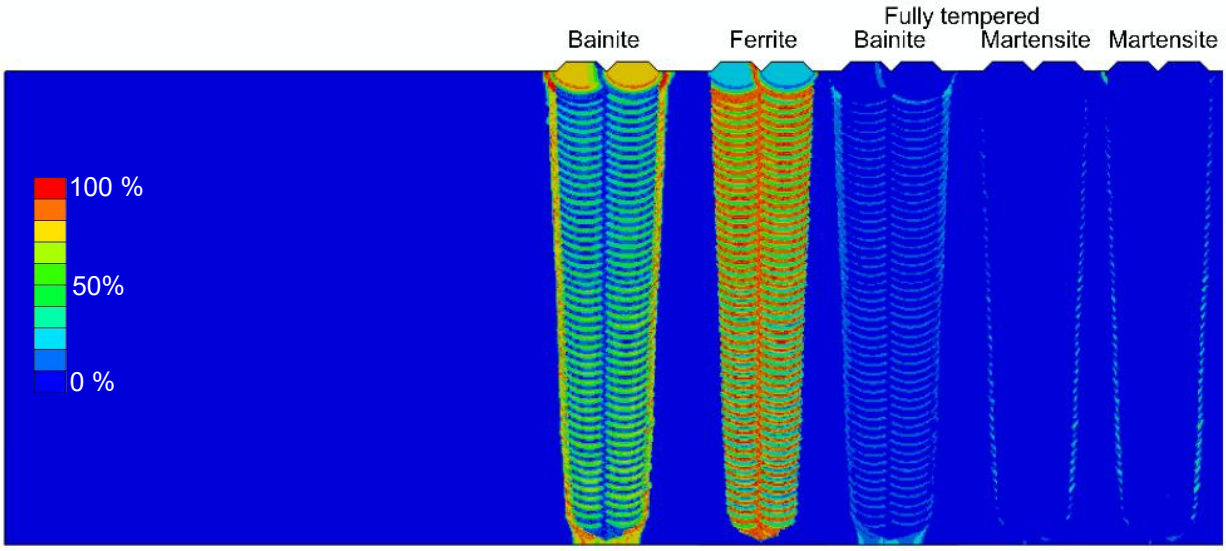

Fig 2. Phases fractions predicted after 103 weld passes. Showing in order bainite, ferrite, fully tempered bainite, fully tempered martensite and martensite.

The Effect of Restraint on Residual Stress Predicted

Fig 3. shows the longitudinal residual stress predicted after 5 passes for the three levels of restrain in a model which does not consider the solid state phase transformations. The peak tensile stress increase with increasing restraint as dose the root peak compressive stress. As can be seen in the inset the free case employs insufficient restraint as the weld grove is already contracting significantly. The springs act to restrain the motion to limit grove contraction. In order to be representative, the springs must be calibrated to the correct stiffness using the grove contraction record from the experimental log.

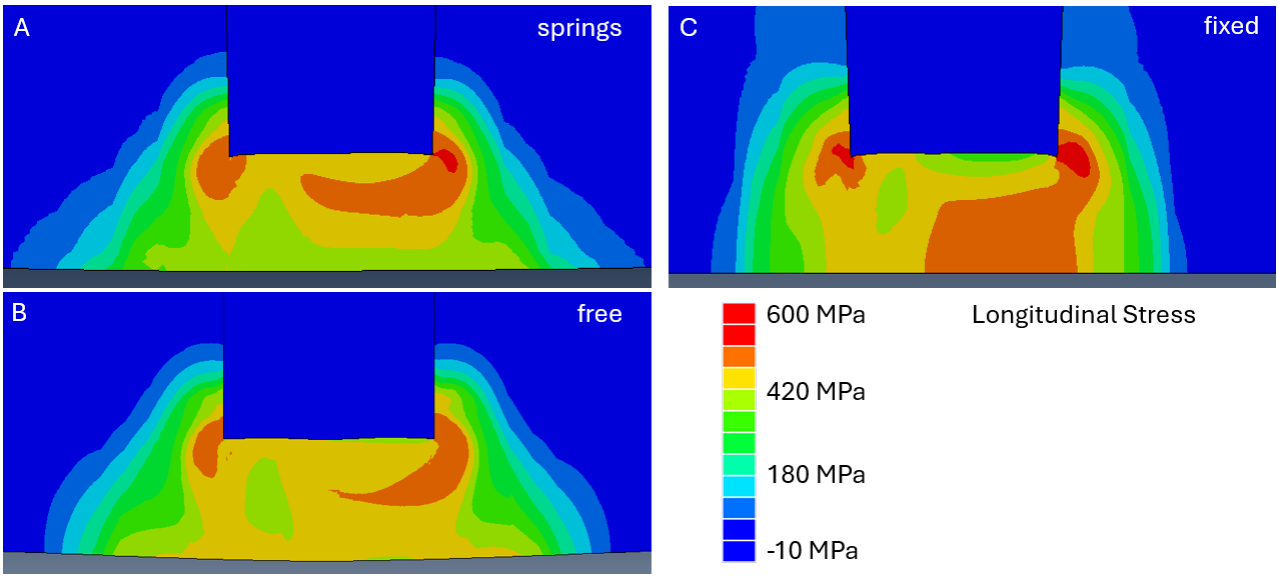

Fig 3. Residual stress after 5 passes with A) spring elements representing the clamps, B) no restraint and C) fixed base.

Summary

The work presented shows the complex solid state phase evolution in high multi pass welds of low alloy steels. This in turn will impact the predicted local residual stress state. The level of restraint is shown to affect the peak magnitude of residual stress predicted, with springs showing promise to represent the experimental restraint rig without over constraint.

[1] D.W. Rathod, J.A. Francis, A.N. Vasileiou, M.J. Roy, P.D. English, J. Balakrishnan, M.C. Smith, N.M. Irvine, International Journal of Pressure Vessels and Piping 172 (2019) 313-328.
[2] Y.L. Sun, C.J. Hamelin, A.N. Vasileiou, Q. Xiong, T.F. Flint, G. Obasi, J.A. Francis, M.C. Smith, International Journal of Pressure Vessels and Piping 187 (2020) 104154.