

Simulation of Multi-Pass Welds Using ABAQUS 2D Weld GUI and Comparison with Experimental Results

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Abstract

The modelling of welds is desirable to predict the distortion of components during manufacture, the position and magnitude of peak residual stresses and to predict metallurgical effects in specific regions. Welds are a complex modelling problem requiring both thermal and structural solutions. This has lead to the development of several weld-specific simulation packages and codes for finite element analysis packages.

This paper describes the application of the newly developed Abaqus 2D Weld Modeller to simulate the residual stress field in ferritic weld test specimens. The specimens were manufactured for an ongoing research programme in conjunction with The University of Manchester and Serco Assurance. The specimens modelled were autogenously welded plates, an eight-pass groove welded plate and a seven-pass ring weld disk.

The 2D weld GUI simplified the creation of these models, particularly with its automated selection of surfaces to apply heat transfer equations to and the model change requirements for weld bead deposition.

The results are similar to both measured and previously modelled stress distributions. Simulations have been performed using a number of tools including Abaqus and VFT. Measurements have been made by The University of Manchester using neutron diffraction. The results are broadly similar, but there are noticeable differences in the fusion zone/weld bead area due to the lack of phase transformation modelling. Phase transformation introduces compressive stress in the fusion zone due to the crystallographic expansion as the steel grains transform from face-centred cubic to body-centred cubic. This compressive region also creates a balancing tensile stress region in the heat-affected zone.

Keywords: Residual Stress, Welding.

Introduction

The modelling of welds is desirable to predict the distortion of components during manufacture, the position and magnitude of peak residual stresses and to predict metallurgical effects in specific regions. Welds are a complex modelling problem requiring both thermal and structural solutions.

This has led to the development of several weld-specific simulation packages and codes for finite element (FE) analysis packages.

These FE packages are part of either larger FE packages such as SYSWELD™, or stand-alone packages such as VFT™, (ESI, 2008 and Battelle, 2006) which can be problematic if further analysis of the component needs to be conducted in an alternative program, eg Abaqus/CAE. The development of a 2D weld simulation tool by Abaqus™ (Simulia, 2010) would allow further analysis of the model within the normal Abaqus environment. As the tool is currently only two dimensional, it has currently limitations but is hoped that this will be developed into a full 3D moving heat source tool.

The work discussed in this paper is part of an ongoing research programme co-ordinated by Rolls-Royce plc in collaboration with The University of Manchester (UoM) and Serco Assurance (Serco) to investigate the development of material and weld modelling techniques.

Weld Modelling

There are several techniques that can be used within FE models to simulate welding. A summary of two of the techniques will be briefly summarised here. The following descriptions cover thermal analyses, the mechanical analyses are generally similar using the thermal models to provide the temperature input which drive the thermal expansion, contraction and changes to material mechanical properties.

The simplest method of weld modelling is known as the ‘Block Dump’ method. The method can be used for 2D or 3D models. The weld beads are deposited as contiguous blocks which introduce a heat flux into the component. This heat flux is allowed to continue until the volume of material above the melting point is equal to the volume of fusion zone. The heat flux is then removed and the component is allowed to cool to the inter-pass temperature before the next weld block is introduced.

This method is simple and quick. It is the only method available for 2D modelling. Block dumping heavily simplifies 3D thermal models but this can be mitigated by breaking a block up into smaller sequential blocks to simulate the progressive deposition of a weld pass, known as ‘Chunking’. Chunking can be combined with ramping of the heat fluxes to simulate how a welding torch would introduce heat into a component.

The most computationally intensive thermal modelling methods is a volumetric moving heat source (Goldak, 2005). The method defines a volume of material as the weld pool which is directed to traverse the model along the weld bead (Figure 1). This weld pool is tuned to be similar in size to the actual weld pool and the heat flux it receives. This can be combined with sequential element activation to simulate deposition of the weld metal. This is the logical extension of the chunking method where the chunks are reduced in size to a single element.

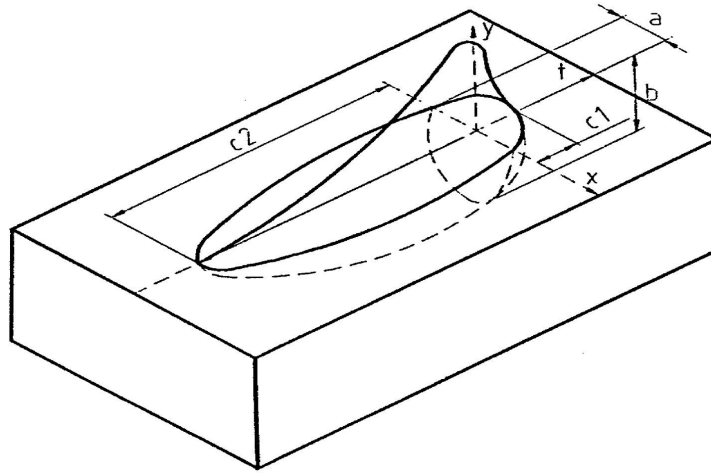


Figure 1: Diagram of The Double Ellipsoid Model by Goldak (Goldak, 2005)

The work by Goldak defines this weld pool volume as a double ellipsoid using the following equations for the front and rear half of the weld pool.

$$q_f(x, y, z, t) = \frac{6\sqrt{3}f_f Q}{abc\pi\sqrt{\pi}} e^{\frac{-3x^2}{a^2}} e^{\frac{-3y^2}{b^2}} e^{\frac{-3[z+v(\tau-t)]^2}{c^2}} \quad \text{Equation 1}$$

$$q_r(x, y, z, t) = \frac{6\sqrt{3}f_r Q}{abc\pi\sqrt{\pi}} e^{\frac{-3x^2}{a^2}} e^{\frac{-3y^2}{b^2}} e^{\frac{-3[z+v(\tau-t)]^2}{c^2}} \quad \text{Equation 2}$$

Where q is the heat flux, x, y, z are the coordinates of model, t is the time, f is the power split factor which can be different for front or rear half of the weld pool but $f_f + f_r = 2$, Q is the effective torch power (electrical power $\times$ efficiency), a, b, c are the dimensions of ellipsoid and can be different for the front and rear half of the weld pool, v is the welding speed and τ is the lag factor to define position at $t(0)$.

This equation allows a realistic weld pool to be translated through a model with control over its dimensions, ratio of power ahead and behind the torch centre, speed and power.

The Goldak moving heat source model can currently be applied using a user sub-routine within Abaqus. This allows the full definition of the weld pool although refinement of the various dimensions and factors is a time-consuming, iterative process. It is currently difficult to implement this user sub-routine approach with sequential element activation.

Specimens and Models

Several different specimens have been modelled during this work (Gill, 2009 and Pellereau, 2010). The analysis is of three specimens using the Abaqus 2D Weld GUI will be discussed in

this paper; autogenously welded plates, eight-pass groove weld and seven-pass ring weld specimens.

The autogenously welded plates were 180×150×20 mm and manufactured from ferritic SA508 Grade 3 Class 1 pressure vessel steel. An autogenous weld bead was introduced along their longitudinal centreline, Figure 2. An autogenous weld does not introduce any weld metal and is created by traversing the weld torch along the specimen. One- and two-pass specimens were manufactured and the residual stresses measured using neutron diffraction (ND). The measured residual stresses are compared with the modelling results.

The eight-pass groove welded plate was a 200×150×20 mm plate and also manufactured from ferritic SA508 Grade 3 Class 1 pressure vessel steel, Figure 2. The plates had a 10 mm deep V-groove machined along their length with a 4 mm radius rounded bottom. The V-groove had a side wall angle of 60°. The groove was filled with Oerlikon SD3 1Mo 1/4Ni weld metal in eight passes. Some of the specimens manufactured were used to investigate the effects of weld stop-start on the residual stress field; however this could not be modelled in 2D.

The final specimen discussed here is the seven-pass ring weld specimen. This was a thick disc with a circular V groove machined into the surface, Figure 2. The disc was 30 mm thick and had a radius of 80 mm. A 10 mm deep V-groove ring was machined into the top surface with a nominal radius of 40 mm. The V-groove had a rounded bottom of 5 mm radius. The V-groove had a side wall angle of 30°. The ring was filled with Oerlikon SD3 1Mo 1/4Ni weld metal in seven passes. All passes were started in the same location (Gill, 2009).

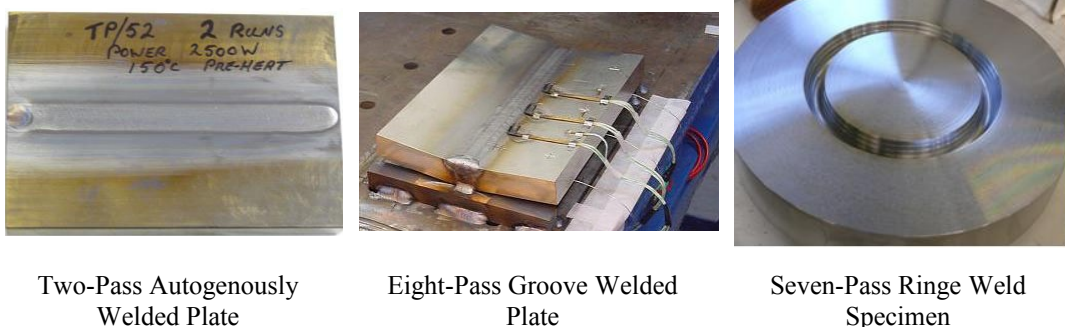


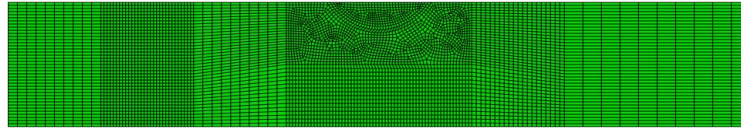
Figure 2: Photographs of Experimental Specimens Modelled using 2D Weld GUI

All the welds were produced using a mechanised Tungsten Inert Gas (TIG) welding head. In the case of the linear welds this head was traversed along a track parallel to the specimens. The circular welds were produced by mounting the specimen on turntable and rotating it at a constant rate with the welding head remaining stationary.

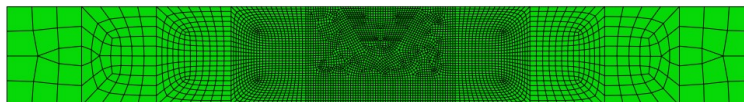
The residual stresses in all the specimens were measured using ND and the results have been used to confirm the accuracy of the FE results.

The models were constructed within Abaqus/CAE and imported into the 2D Weld Modeller. Both quadrilateral and triangular heat transfer elements, DC2D4 and DC2D3, were used for the thermal models, see Figure 3. A generalised plane strain model was used for the mechanical analysis of the plates with element types CPEG4R and CPEG3. For the one- and two-pass autogenous models 4,676 and 5,722 elements were used respectively. The eight-pass groove weld model used 4,925 elements.

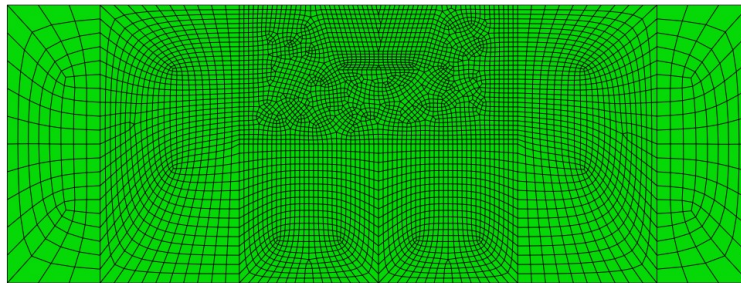
The ring weld model used axisymmetric thermal and mechanical elements (DCAX3 and DCAX4 thermal elements and CAX3 and CAX4R mechanical elements). A total of 4,838 elements were used.



Two-Pass Autogenously Welded Plate



Eight-Pass Groove Welded Plate



Seven-Pass Ring Weld Specimen

Figure 3: Finite Element Meshes Used for Modelling

2D Weld Modeller

The 2D Weld Modeller is a new plugin for Abaqus/CAE 6.10 and allows the rapid construction of 2D weld models. The modeller imports a basic meshed part (a meshed part with no boundary conditions, loads or interactions) with materials and sections defined and allows the user to create the weld beads. The modeller can automatically define weld passes based on the weld bead order and assign surface film and radiation heat transfer properties. The GUI also automates the creation of weld passes based on the naming structure of the weld beads, a set named 'Bead-1' is automatically defined as 'Pass-1' and is the first weld applied to the model. This automation significantly speeds up the process of model creation as one of the most time consuming aspects is the surface definitions for heat transfer coefficients. This allows multi-pass model to be rapidly created.

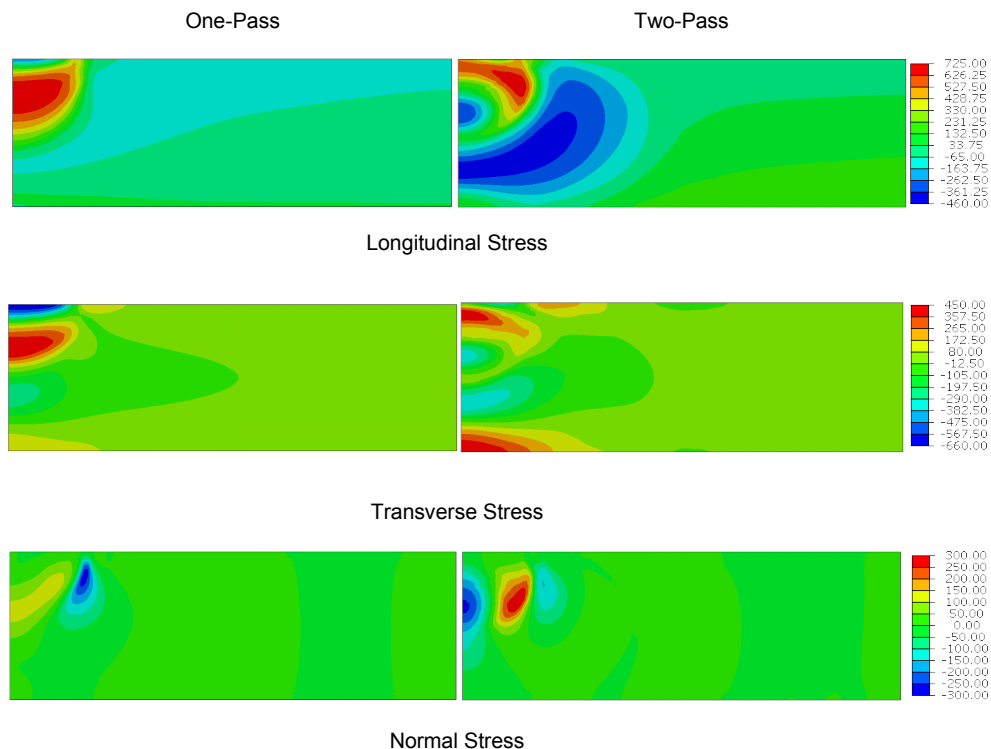
The weld modeller also automates the creation of the thermal and mechanical models and the necessary input decks. This includes the addition of ***model change** flags which previously had to be manually inserted into the input deck.

The method used for controlling the heat flux within the thermal model is defined by the fusion boundary. The weld modeller uses sensor nodes within the mesh, which are defined at a specific

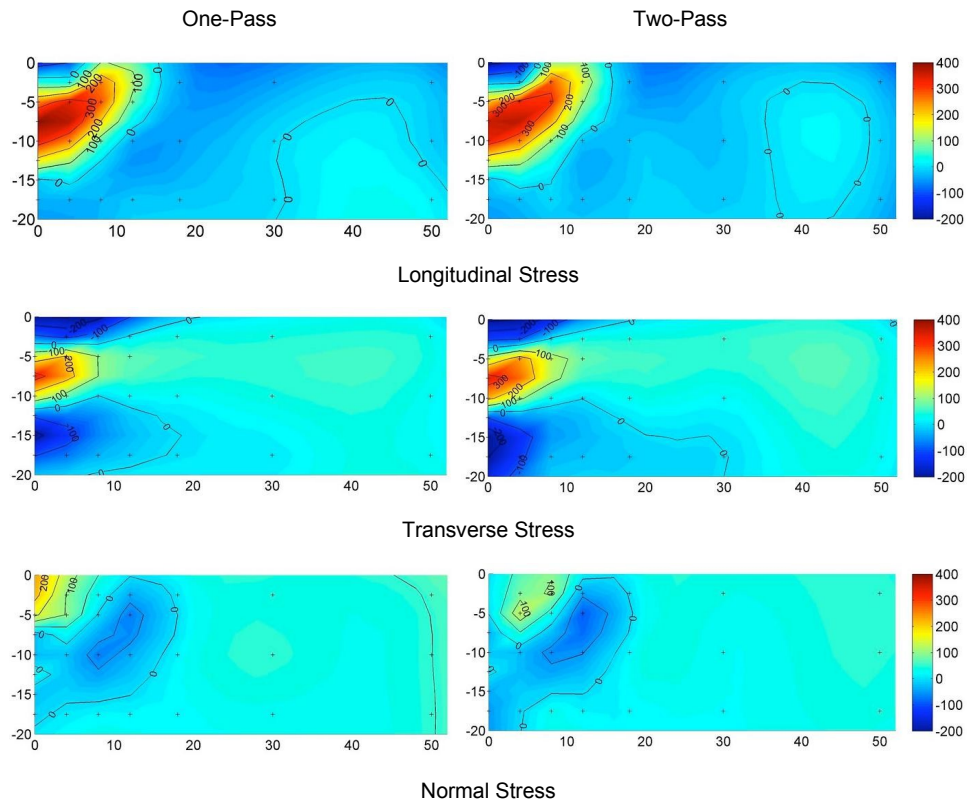
depth. These nodes are then used to end the heating step when their average temperature reaches a predetermined limit. For the models described in this paper the limit was set to 1500°C, the melting point of the weld metal and parent metal, with the sensors located at the edge of the fusion boundary.

Results

Figures 4 and 5 show the one- and two-pass autogenously welded plates FE stress predictions and ND stress measurement results respectively. The FE contour plots presented in this paper have been cropped to allow easier comparison with the ND stress measurement results. The FE results for the one-pass plate are similar to the ND results. The FE results for the two-pass specimens are significantly different to the ND measurements. The ND data indicates that there is region of compressive longitudinal and transverse stress in the weld bead. This is caused by the phase transformation and subsequent volumetric expansion of the crystals as the molten metal converts from Face-Centred Cubic (FCC) austenite to Body-Centred Cubic (BCC) ferrite/bainite/martensite. The effect of this transformation is to move the tensile stress region into the Heat-Affected Zone (HAZ) away from the surface. This effect can be seen in Figure 6 which shows the modelling results using the VFT weld simulation software with phase transformation material properties for SA508 Grade 3 Class 1. These results show the formation of the compressive residual stresses in the weld bead and the corresponding tensile residual stress in the HAZ.



**Figure 4: FE Results For One- and Two-Pass Autogenously Welded Plates,
Stresses are in MPa**



**Figure 5: Neutron Diffraction Results for One- and Two-Pass Autogenously Welded
Plates, Stresses are in MPa**

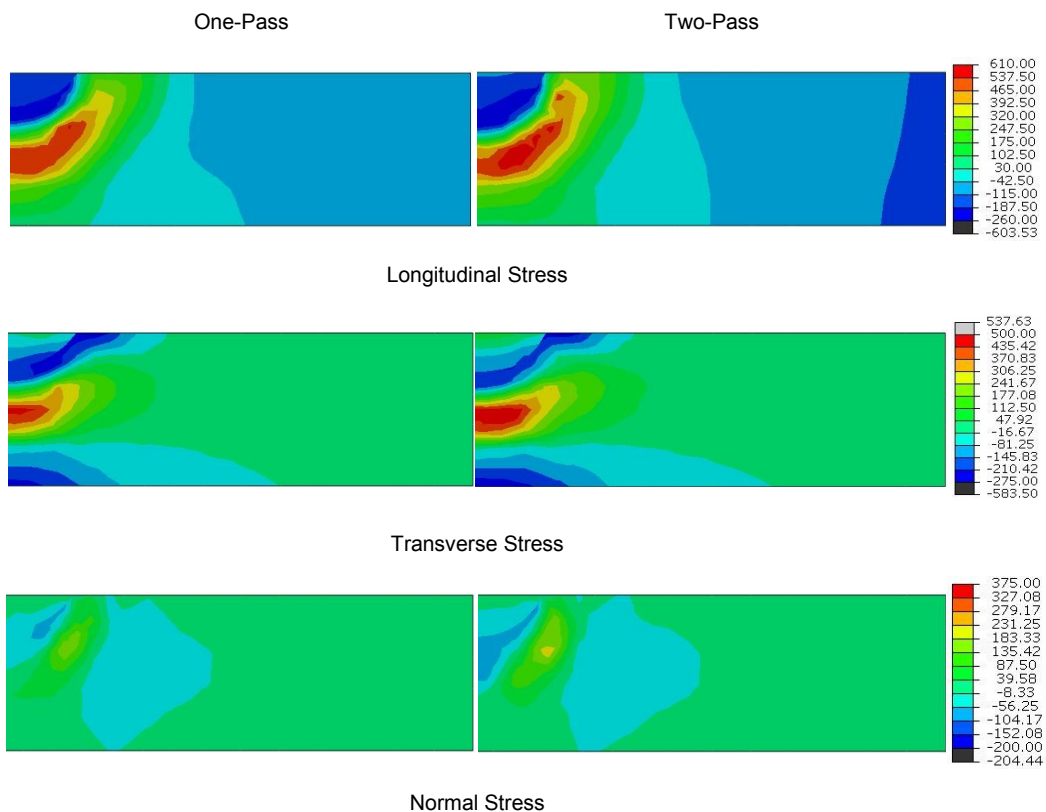


Figure 6: FE Results for One- and Two-Pass Autogenously Welded Plates using VFT Weld Simulation Software with Phase Transformation Material Properties, Stresses are in MPa

Figures 7 and 8 show the FE and ND results for the eight-pass groove weld specimen. The shapes of the contours are very similar with a tensile longitudinal stress region and compressive transverse stress region within the plate. The peak tensile values shown in the ND measurement are generally lower than those predicted by the FE result. This is thought to be due to the FCC to BCC phase transformation that occurs as the weld bead is initially laid down. This creates an offset in the ND stress results as subsequent passes causes the thermal expansion and contraction of that bead.

Figure 9 shows the results of a full 3D VFT welding analysis using a phase transformation material model. This analysis had stop/starts inserted in the fifth pass one-third and two-thirds along the pass. These effects are local increases in the residual stresses. The effects of these can be seen in Figure 9 and highlight the need for 3D modelling tools as these stop/start effects can only be simulated using a 3D model. This model also uses phase transformation modelling which modifies the residual stress field by introducing compressive residual stress into weld bead and fusion zone similar to the effects shown in Figure 6 for the autogenously welded plates.



Longitudinal Stress



Transverse Stress



Normal Stress

Figure 7: FE Results for the Eight-Pass Ferritic Groove Weld Plate, Stresses in MPa

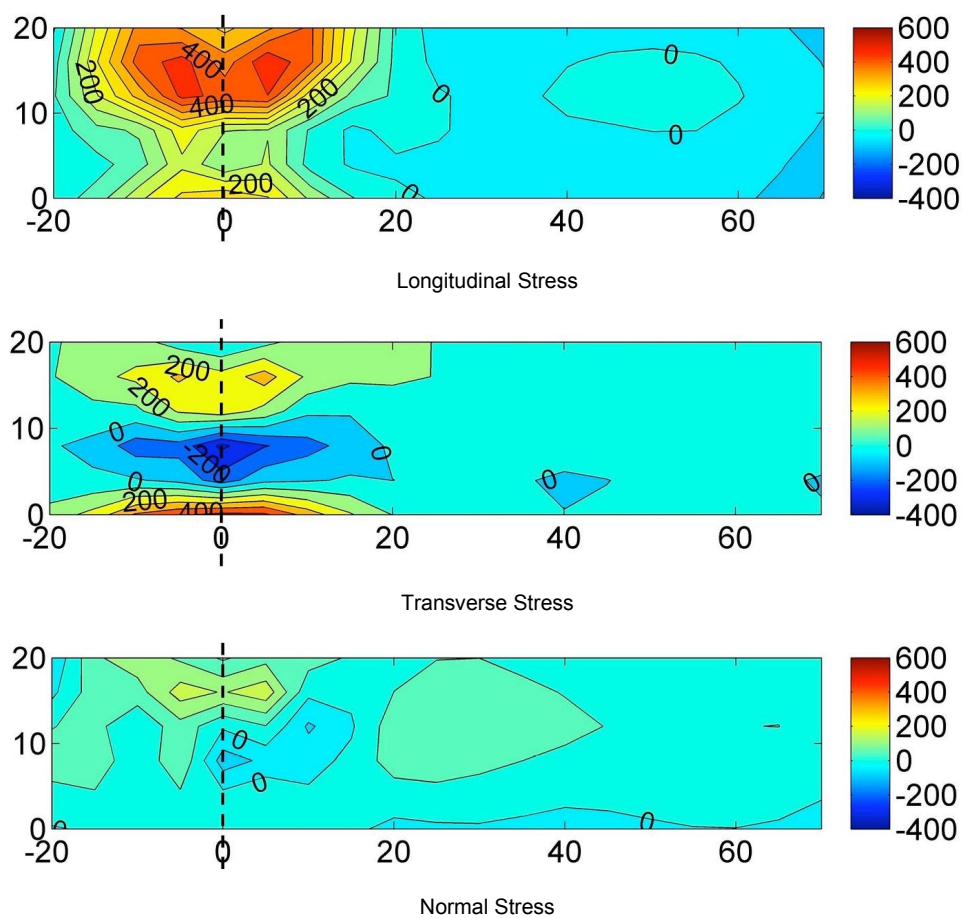


Figure 8: Neutron Diffraction Results for the Eight-Pass Ferritic Groove Weld Plate, Stresses in MPa

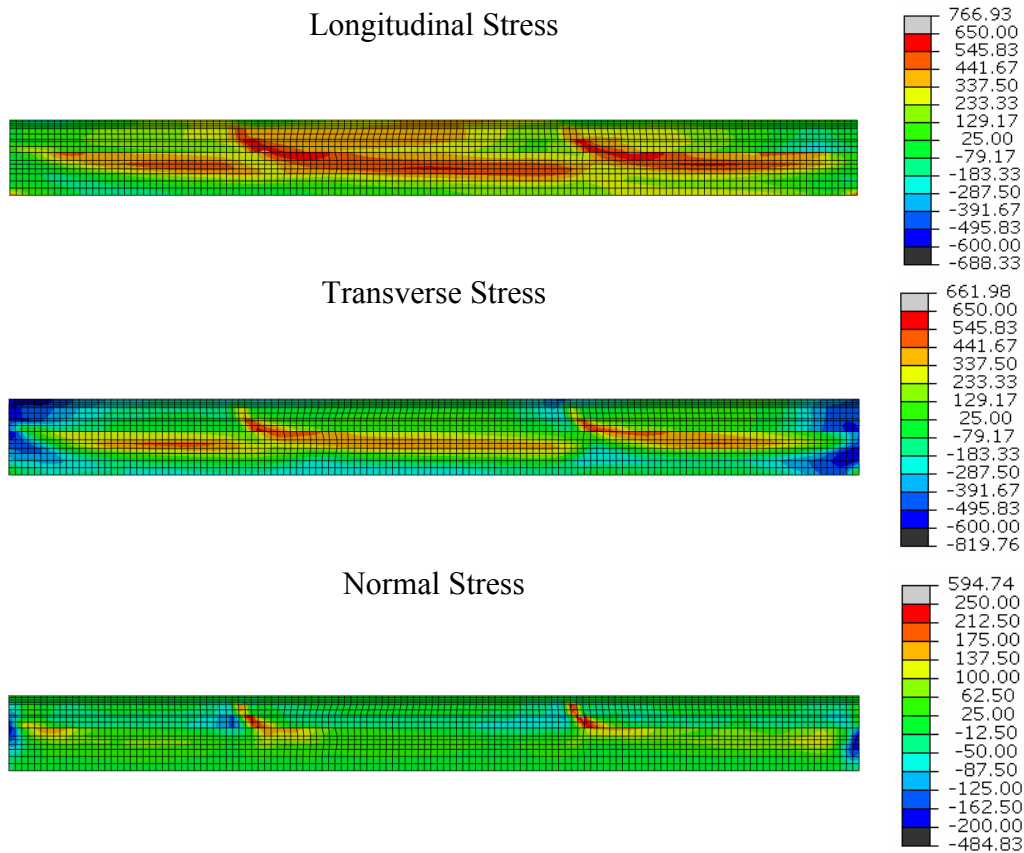


Figure 9: Residual Stresses Along a Longitudinal Cut-Plane showing Stop/Start effects in the Fifth Weld Pass modelled using VFT, Stress in MPa

The FE and ND results for the seven-pass ring weld specimen are shown in Figure 10. The contours do not correlate between the simulation and measurements for two reasons. First, the model was axisymmetric which will over predict the stresses due to the simultaneous contraction of the whole molten weld bead ring within the model, while the reality will be that the torch moves circumferentially round and the contraction occurs sequentially. Second, the lack of phase transformation material properties to create the compressive stress region in the weld beads is noticeable. This effect is larger in this specimen due to the higher constraint which reduces the ability for distortions to relieve the stress. This locks the stress in as residual stress.

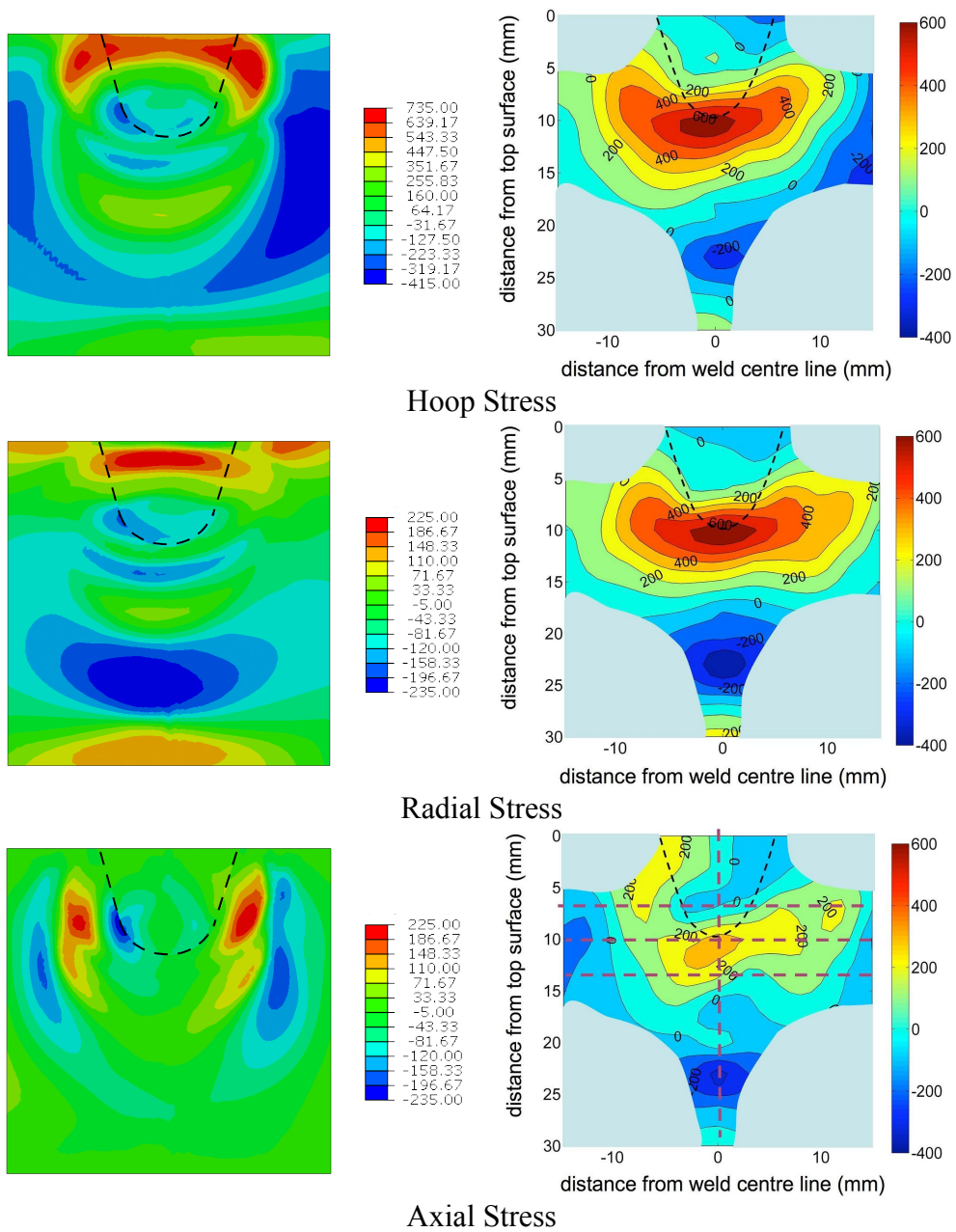


Figure 10: FE and ND Results of the Seven-Pass Ring Weld Specimen, Stresses in MPa

Conclusion and Discussion

The new weld GUI is a significant improvement in Abaqus' native weld modelling capabilities. It allows rapid simulation of simple component geometries. The similarity of the measured and modelled results for the one-pass autogenously welded plate demonstrates the potential of the GUI. The other models described within this paper highlight the current limitations of the weld modeller GUI. For ferritic weld modelling more complex material models are required that include phase transformation effects. Other problems such as the eight-pass groove weld require a 3D modelling technique.

The advantages of the tool were that creation of a weld model was simplified through the automation of the weld pass and heat transfer surface definitions. The models that were created ran quickly as they were 2D models. Improving the modeller to create 3D models will significantly increase the model run time, however this is a necessary development for more complex component geometries. The creation of 2D models is adequate and generally produces conservative residual stress modelling results. Obviously better estimates can be produced with 3D models however there still exists a certain amount of uncertainty about the accuracy of these modelling results.

The lack of built-in advanced material models within Abaqus such as phase transformation models is a problem with weld modelling. This is shown in the ring weld results; the lack of phase transformation modelling creates a significantly different stress field.

Overall the 2D Weld Modelling Tool is useful development of Abaqus/CAE. Its continued development into a full 3D moving heat source model is desirable and should be conducted in conjunction with advanced weld material modelling tools.

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