UK Research Programme on Residual Stresses – Review of Progress

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ABSTRACT

Finite element analysis is being increasingly used to determine the magnitude of residual stresses in welded components. However, there is little guidance available on the accuracy of approaches, especially where simplifications have to be made because of the longevity associated with carrying out 3D finite element analysis. Similarly, experimental methods for characterising residual stresses have their limitations. However, when the two approaches are combined and the results corroborate then the resulting stresses can be confidently used for assessment. A long term UK research programme aims to develop improved guidance on residual stress modelling techniques which will be incorporated into the R6 fracture assessment procedure.

INTRODUCTION

A long-term UK research programme on residual stresses [1] was launched in 2004. It involves Rolls-Royce plc and Serco Assurance, supported by UK industry and academia. It is aimed at progressing the understanding of weld residual stresses and the implementation of finite element simulation and residual stress measurement for assessing the integrity of engineering structures. The main focus in the first couple of years has been to develop detailed guidance on residual stress modelling which will allow the beginnings of the first UK procedure on residual stress modelling to be produced.

The programme has also developed in the following generic areas:

- Weld process modelling
- Residual stress measurement
- Knowledge/Information gaps
- Residual Stress mitigation (Weld design)
- Guidance on the prediction of residual stresses
- Evaluation of data and validation of predictive methodologies
- Technology watch

In the first instance, work mainly concentrated on austenitic, latterly ferritic weldments have been investigated. Once sound modelling techniques have been developed for these materials, work will progress to transition welds and other materials of interest. This paper presents an overview of the work that has been carried out to date within the research programme.

WELD PROCESS MODELLING

It is recognised that fully modelling the thermal and thermo-mechanical processes associated with welding is extremely complex, but for practical considerations the heat flow solution for determination of residual stresses and distortions can be simplified by considering the fusion profile as a known quantity [2]. This approach has been largely adopted whereby a heat source model, e.g. due to Goldak [3], is calibrated by ensuring that it produces the desired weld fusion profile, which is usually obtained from a weld macrograph. One of the earlier issues identified for investigation was the heat source representation and how it affected the predicted temperatures and subsequently the weld residual stresses.

There are several simplifying techniques available to reduce the run-time and modelling complexity when analysing multi-pass welds, e.g. prescribed temperature methods, bead lumping and bead dumping. When results are obtained from these simplified analyses, it is important to be able to judge whether the results are (i) conservative or non-conservative, and (ii) by how much. The modelling of an austentic pipe circumferential butt weld [4] and an austenitic multipass groove weld [5] have been used to develop and refine finite element techniques used to predict weld residual stresses. The sensitivity of predicted residual stresses to simplified modelling assumptions [6] was considered for an austenitic bead on plate specimen, which is one of the benchmarks being studied within the NET European network [7]. Modelling of an autogenous weld along a ferritic beam [8] has been carried out to develop a material model and to understand the effect of phase transformations on the residual stresses present within welded ferritic structures.

DESIGN AND MANUFACTURE OF WELDED MOCK-UPS

The validation of the modelling techniques is essential for developing confidence in their use. Significant efforts have been made during the first two years of this programme to generate experimental data for the validation of weld mock-ups. The initial programme [1] identified the following mock-ups for study:

- Austenitic single bead on a flat plate
- Austenitic multi-pass weld in a groove on a flat plate
- Austenitic plate butt weld
- Austenitic pipe butt weld
- Ferritic autogeneous welded beam specimen
- Ferritic single bead on a flat plate
- Ferritic multi-pass weld in a groove on a flat plate
- Ferritic plate butt weld
- Ferritic pipe butt weld

The materials are those of particular interest to the programme. The initial geometries to be considered are generic, i.e. plate, pipe, etc in order to establish the modelling techniques that will be later employed for the analysis of more complex arrangements. The modelling of the welding process is simplified further by considering an autogenous weld, in order to account for the effects of material phase changes on residual stresses, and single bead welds, in order to validate the fundamental modelling representations of the heat source and material behaviour.

During the manufacture of these specimens, thermocouples and strain gauges will be attached at key locations, which will be decided by supporting finite element design analyses. Some specimens will be sectioned to allow both transverse and longitudinal macrographs to be produced. More detailed metallography will be carried out on a selection of these sections, particularly for the ferritic specimens to identify material phases. Other specimens will need to be reserved for the measurement of residual stress. Examples of the mock-ups manufactured to date are described in the following sections.

Austentic Welds

The programme recognizes that there are world-wide activities, such as PVRC (Pressure Vessel Research Council) and IIW (International Institute of Welding) that involve significant research activities in the area of weld residual stresses. Collaboration and/or links with these activities will be of mutual benefit in order to maximize findings and reach agreements on the best methodologies to employ. Thus the first example listed above, see Figure 1 below, considered the sample used in the European NeT programme.

Figure 1: Austenitic bead on Plate Specimen Developed by NET program

Participation in these round-robin events allows greater information to be established as participants offer both analytical predictions and measurements which can provide valuable validation on the methods used.

A comparison of the modelling results from the NeT programme has shown that despite each of the participants matching the weld macrograph, differences arose between the predicted temperatures at various thermocouple positions. This occurred due to the different assumptions that were made with respect to the heat input and, as was later found, a difference between the reference weld macrograph and the supplied test welds. Clearly, any assumptions relating to the weld heat input will affect the predicted stresses, as will the choice of material hardening model, and the assumptions associated with the annealing behavior of the material during the deposition of subsequent weld passes.

The second example is an Austenitic multi-pass V-groove weld in a flat plate, see Figure 2.

Figure 2: Multi-pass V-groove Specimen with thermocouples attached.

Several specimens have been manufactured in order to study the effects of different types of weld stop-starts on the weld residual stresses. Diffraction based measurements on these specimens have allowed the effects of abrupt as well as ramp down stop-start effects to be quantified. Furthermore, the annealing effects of subsequent weld passes laid down on top of the weld interruptions has also been investigated.

Ferritic welds

Analysis of a ferritic beam specimen has been carried out to examine the effects of phase transformations on the magnitude and distribution of residual stress. The specimen is a 250mm x 10mm x 50mm plate that has been autogenously TIG welded along the top surface, see figure 3. In this process a weld torch is passed along the edge of the beam, but no additional weld material is introduced. A major advantage of this specimen configuration is that it avoids the complexity of modelling the addition of weld material.

Initial scoping calculations [8] examined how differing weld speeds affected the phase transformations within the material as well as the predicted residual stress distribution. The stresses were sensitive to the effects of phase transformations especially in the region of the weld. On the basis of these calculations, initial specimen mock-ups were manufactured from SA508 ferritic steel in order to assess whether the welding parameters used in the analysis were physically feasible in terms of producing an acceptable weld bead. The run on/off plates, shown in Figure 3, were found to be required when a high current and fast weld speed were used.

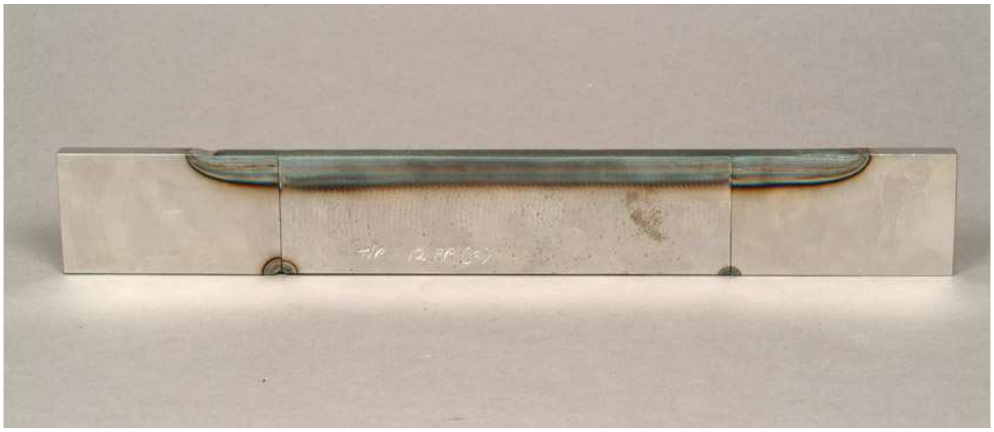

Figure 3: Autogenous welded beam specimen (with run on and off plates tack welded at each end)

Examination of the HAZ microstructure showed some effect of the cooling rate, which was varied by adjusting the heat input and torch speed. The faster cooling rate resulted in an increased proportion of martensite mixed with the bainite in the HAZ. Sin the near future, residual stresses in the beam specimen will be measured using synchrotron and neutron diffraction techniques and the results will be compared with predictions

A study has started to investigate the effects of different welding parameters, see Table 1, on the residual stress distributions for the simple configuration of a single bead-on-plate specimen shown in Figure 4.

Table 1: Matrix of Tests on Ferritic Bead-on-plate Tests

Experiment No.	**Heat Source Power (W)**	**Travel Speed (mm/min)**	**Preheat Temp. (^oC)**	**Wire Feed Speed (mm/min)**
1	2000	75	150	1000
2	**1500**	75	150	1000
3	**2500**	75	150	1000
4	2000	**50**	150	1000
5	2000	**100**	150	1000
6	2000	75	**250**	1000
7	2000	75	150	**700**
8	2000	75	150	**1400**

Note the numbers in bold represent the changes to the base case conditions in Experiment number 1.

Figure 4: Ferritic Bead-on-Plate Specimen

Each of the plates was 20 mm thick, and measured 180 x 120 mm. The plate thickness was carefully chosen so that the plate did not distort excessively during welding. At the same time, if the plates were too thick it would have been difficult to make non-destructive stress measurements by neutron diffraction. All the specimens were produced using mechanized TIG welding with a low-alloy steel solid wire filler material.

Residual Stress Measurements

The residual stresses in each of the mock-ups will be measured using a variety of techniques. Table 2 provides a summary of the welded mock-ups manufactured to date and the proposed measurement techniques which will be applied. Surface measurements will be obtained using X-ray and hole drilling methods, whilst through-wall measurements will use a combination of techniques such as neutron and synchrotron diffraction, deep hole drilling and contour method in order to map stresses at sections of interest.

Table 2: Status of Welded Mock-up Specimens for Residual Stress Measurements

Specimen Type	Thermocouple Data	Stress Measurements					Mitigation Studies (PWHT or Peening)
		Neutron Diffraction	Contour Method	Synchrotron or X-Ray Diffraction	MAPS	Deep Hole Drilling	
8-Pass Austenitic Groove Weld	C	I	I	P			P
Ferritic Bead on Plate	P	C	P	P	I	P	
Ferritic Melt Edge Beam	P	P	P	P	P		

Key

C = Completed, P = Planned, I = In Progress, U = Unrestrained Edges, R = Restrained Edges

Austenitic material is a 304 stainless steel plate and 308 TIG filler metal
Ferritic material is a SA508 steel plate and SD3 low carbon TIG filler metal

Residual stress measurements have been carried out on six of the bead on plate samples', see Table 1, using the neutron diffraction facilities at the FRM2 research reactor in Munich. Measurements were made on a plane transverse to the welding direction and at the mid-length of the weld. In order to obtain the maximum resolution in stress within the time available, it was assumed that the stress distribution would be symmetrical about the weld centerline. An example of the transverse stresses that were measured in one of the samples (condition 1 in Table 1) is given in Figure 5. The origin in the coordinate system shown corresponds to a position approximately in the centre of the weld bead, and on the original plate surface. The vertical axis corresponds to the weld centerline.

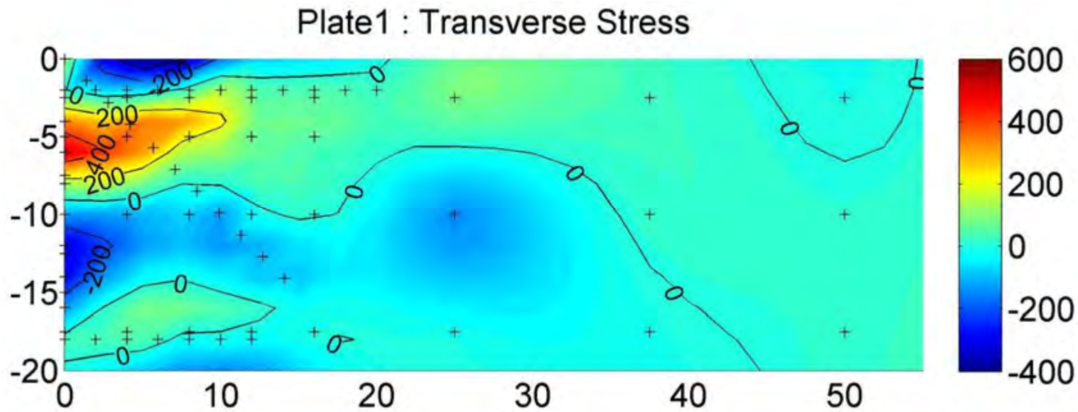

Figure 5: Transverse stresses measured in plate 1. The origin corresponds to the centre of the weld bead and the measured stresses are in MPa.

MATERIALS DATA

The modelling and interpretation of residual stress measurements requires supporting materials data and an initial review identified a suitable materials testing programme. This programme is currently generating tensile and cyclic data for SA508 material and weld metal from room temperature up to 700°C. Physical properties (conductivity, density, thermal expansion, specific heat, thermal diffusivity) have also been generated up towards melting temperature. Creep tests have also been carried out between temperatures of 500 and 700°C in order to study the stress relaxation behaviour during post weld heat treatment (PWHT).

Part of this work is the comparison of test data that is being generated both from conventional test and miniature 'matchstick' specimens. The matchstick specimens are 40mm long with a 1.5 x 1.5 mm cross section which are tested on a Mark 1 Electro-Thermo-Mechanical Testing (ETMT) system. The strains are determined through a correlation with the resistance measured in the central region (typically 2-3 mm) of the specimen. The interest in using matchstick specimens is that they can be extracted from an approximate single bead region with a TIG weld. This is not possible with conventional test specimens that have a greater cross section.

Matchstick specimens have also been used to generate a continuous cooling transformation (CCT) curve for SA508 ferritic steel, see Figure 6. In these experiments the phase transformations were characterized using in-situ synchrotron X-ray diffraction.

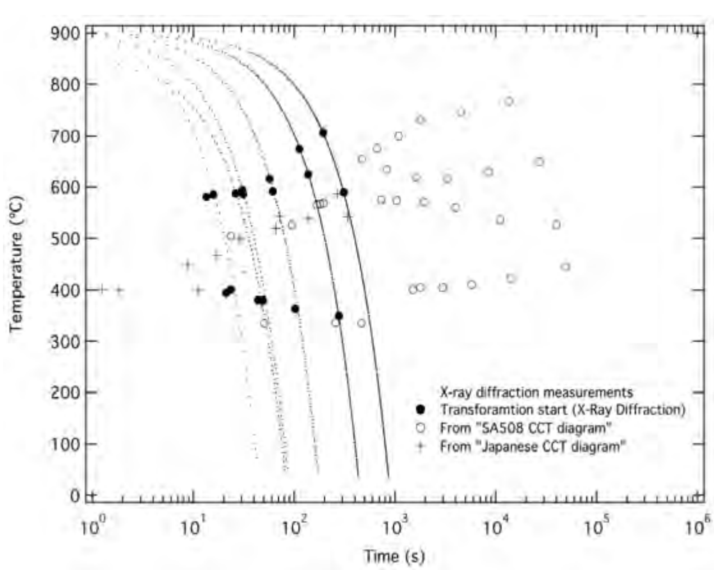

Figure 6: Portion of the CCT curve for SA508 steel as determined by X-ray diffraction. The points indicate the commencement of transformation. The differences between the data sets are attributable to differences in prior-austenite grain sizes.

WELD DESIGN/RESIDUAL STRESS MITIGATION

The objectives of this work are:

(i) To improve design of welded structures in order to reduce and control the evolution of residual stresses and product distortion during fabrication, assembly, machining and surface treatment.

(ii) To improve fabrication techniques in order to reduce and control the magnitude of residual stresses.

(iii) To improve maintenance procedures so that any detrimental effects (i.e. increases in residual stress) associated with in-service repairs are minimised.

A review of residual stress mitigation methods for application in nuclear power plant [9] identified several techniques which may be beneficial and warranted further development. Mitigation studies are planned to investigate the effect of various peening methods (laser jet, water jet and ultrasonic impact treatment) on weld residual stresses. Further studies will investigate the effect of PWHT on weld residual stresses using ring weld specimens.

WELD MODELLING PROCEDURE/GUIDELINES

Whilst many articles have been published that illustrate the use of finite element and numerical analysis techniques to predict residual stresses, there remains no common procedure for identifying the best techniques to employ or how simplified analyses may affect predictions. The development of a procedure/guidelines, which will be incorporated in the a future issue of the British Energy R6 defect assessment procedure [10], has been achieved through collaboration between British Energy, Rolls-Royce, Serco Assurance and Fraser Nash Consultancy on the basis of significant plant experience and collaboration with world-wide activities.

A step by step procedure has been designed which assists the analyst with the choices they need to make on deciding the initial modelling approach, as well as providing guidance on the subsequent finite element modelling and analysis, with advice on the level of verification required. At each step support is provided in the form of extensive advisory notes which provide details to assist in making these choices.

The first step relates to the structural performance concern as this determines the weld simulation objectives. The nature of the structural performance concern can be characterized by the type of degradation mechanism (creep, fatigue, stress-corrosion, ductile or brittle fracture etc), the stage in the degradation life cycle (defect initiation, stable crack growth, leak-before-break, unstable crack growth), the nature of the defect (size, shape, location, orientation and morphology), as well as the structural context, materials, environment and service loadings. Weld residual stresses exist at length scales ranging from nanometres to several metres in engineering structures. It is self evident that the length scale for residual stress modelling and measurement studies should be determined primarily by the nature of the specific structural performance [11]. Once the relevant length scale is established the appropriate finite element analysis parameters can be chosen.

The second step concerns the collection of input data based on the procedural requirements. This lists the ideal information required for carrying out a welding simulation using finite element analysis. It includes information on the weld geometry, welding process and procedure, macrographs, welding sequence, pre-heat /interpass temperatures and fabrication records which would indicate whether any restraints or long range mechanical effects may need to be accounted for. Thermal and mechanical properties are then listed indicating the temperature range (from room up to melting temperature) over which they are required.

The third step is the consideration of available resources. This covers the selection of suitably experienced personnel, software requirements and computing hardware requirements. It is recognized that the analyst needs to be capable of carrying out complex thermal transient elastic plastic stress analyses and also requires an appreciation of the physical and metallurgical processes associated with welding and the significance of the resulting residual stresses. The software requirements recognize the features pertinent to finite element residual stress modeling which are not standard features in all finite element codes. These include the addition of filler material, heat source modelling tools, material hardening/softening models and annealing. These requirements need to be considered in combination with the time and money available for the analysis, i.e. 2D models may need to be used for a quick result or when funding is insufficient for a detailed analysis, which would consume most of the available resources.

Using the information obtained from Steps 1 to 3 a decision is then made on which modelling approach to use (Step 4). A flow chart is provided which may be used to define which of the six available analytical options is best suited for the requirements in Step 1. Following this decision, a second flow chart can be used to decide if there is sufficient information to carry out the analysis indicated in Step 1. If there is insufficient information then the user should either recommend more work to acquire the information or choose the option of a simpler analysis. A similar decision will then need to be made on the basis of the resources available to the user.

The next three steps guide the user through the finite element modelling, thermal and mechanical analysis and validation. The Advisory Notes provide information on model idealisation, heat source representation and the addition of filler material. The six analytical options relate to the use of simpler 2D planar models through to complex 3D moving torch models. Advice is provided on the use of block lumping and block dumping methods, which may be used to represent the addition of filler material.

The treatment of plastic strain hardening in the mechanical analysis can have a very important influence on the detailed distribution and degree of conservatism in the predicted stresses [6, 12]. Tables are provided which give the analyst key information about the property requirements for three material constitutive models:

- Isotropic hardening
- Kinemetic hardening (non-linear)
- Mixed kinematic-isotropic hardening.

The tables also describe how to implement the models from which an assessment of the costs/benefits of increasing complexity can be made.

The final section relates to validation of the predicted results. A high standard of validation may be attained by comparison with measurements from a full size mock-up that closely represents the structural weldments of concern. These measurements should include transient temperatures using thermocouples, a weld macrograph and residual stresses measured using at least two diverse techniques, e.g. a stress-relaxation method and a diffraction-based method.

It is recognized that such high standards of validation are often not possible due to constraints such as time and cost, so advice is provided on the use of diverse validation benchmarks for comparison with published measurements, both of which closely relate to the structural weldments of concern. Validation benchmarks are to be included in the procedure to assist the analyst with this task.

CONCLUSIONS

The three main themes within the residual stress programme are measurement, modelling and mitigation of residual stress. In the first 2 years of the programme, the research has concentrated on the numerical modelling of weld residual stresses, using the finite element method, although some aspects of residual stress measurement and mitigation have been covered. It is expected that the emphasis will shift towards the measurement and mitigation aspects of residual stress during years 4 and 5 of this (initially) 5 year programme.

This is consistent with the overall aims of the research which are:

- To provide a procedure for the calculation of residual stresses in welded joints using finite elements.
- To provide methods and tools to mitigate against residual stress in welded joints.

ACKNOWLEDGEMENTS

The authors would like to thank other members of the collaboration at British Energy and Fraser Nash Consultancy in the development of the residual stress modelling guidelines procedure, University of Manchester for their assistance in residual stress measurements and the development of the CCT diagram, and the National Physical Laboratory (NPL) for the testing of miniature tensile matchstick specimens.

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