

# Numerical Welding Simulation on a 14" Narrow Gap Dissimilar Metal Weld

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## 1 ABSTRACT

AREVA NP has developed narrow gap weld techniques to perform junctions between ferritic low alloy steel heavy section components and austenitic stainless steel piping systems. In parallel, numerical welding simulation has already demonstrated its relevance to predict residual stress fields in welded components.

This paper presents computations on a 14" narrow gap Dissimilar Metal Weld (DMW) configuration. The analysis simulates each elementary step of the mock-up manufacturing procedure. Multipass welding simulation reproduces the deposit of each bead by thermo-metallurgical and mechanical calculations. The main original points of the work are:

- The choice of non linear kinematic hardening models,
- The use of strain annealing and phase transformation techniques,
- The post weld heat treatment simulation.

For validation, the numerical results are compared to measurements obtained by both neutron diffraction and deep hole drilling techniques. The residual stress fields are observed at various locations from the weld centreline, in the depth of the pipe, and a very good agreement is obtained.

Within the framework of narrow gap DMW configurations, this work gives another evidence of the relevance of the numerical welding simulation and highlights the capability for AREVA NP to perform, with success, such a kind of analyses.

## 2 INTRODUCTION

Welding remains a key process in joining metallic pieces. In nuclear reactors, ferritic low alloy steel heavy section components have to be connected with austenitic stainless steel piping systems. Special manufacturing procedures are required to ensure a good resistance of the Dissimilar Metal Weld (DMW). In the field, AREVA NP has developed narrow gap weld techniques to perform these junctions.

In parallel, numerical welding simulation has already demonstrated its relevance to predict residual stress fields in welded components and becomes more and more a real support for industrial design engineers (Courtin and Gilles 2006 and 2007).

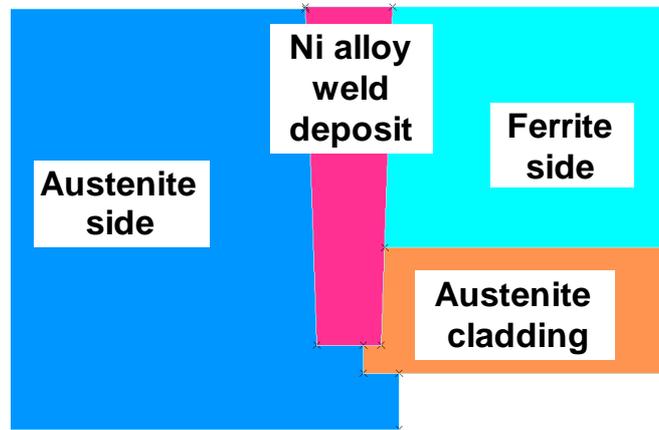
This paper presents computations performed by AREVA NP on a 14" narrow gap DMW configuration. Considering 2D axisymmetric hypotheses, the analysis simulates each elementary step of the mock-up manufacturing procedure. Multipass welding simulation reproduces the deposit of each bead by thermo-metallurgical and mechanical calculations. The main remarkable points of the work will be detailed later.

For validation, the numerical results are compared to measurements obtained by two different ways: neutron diffraction (Hutchings et al. 2005) and deep hole drilling (Leggatt et al. 1996, Kingston et al. 2006) techniques. The residual stress fields are observed at various locations from the weld centreline, in the depth of the pipe.

In this paper, the mock-up manufacturing procedure will be first summarized, following by a short description of the residual stress measurements. After the finite element assumptions will be explained. Finally, comparisons between experimental and numerical results will be detailed and discussed.

### 3 MOCK-UP MANUFACTURING PROCEDURE

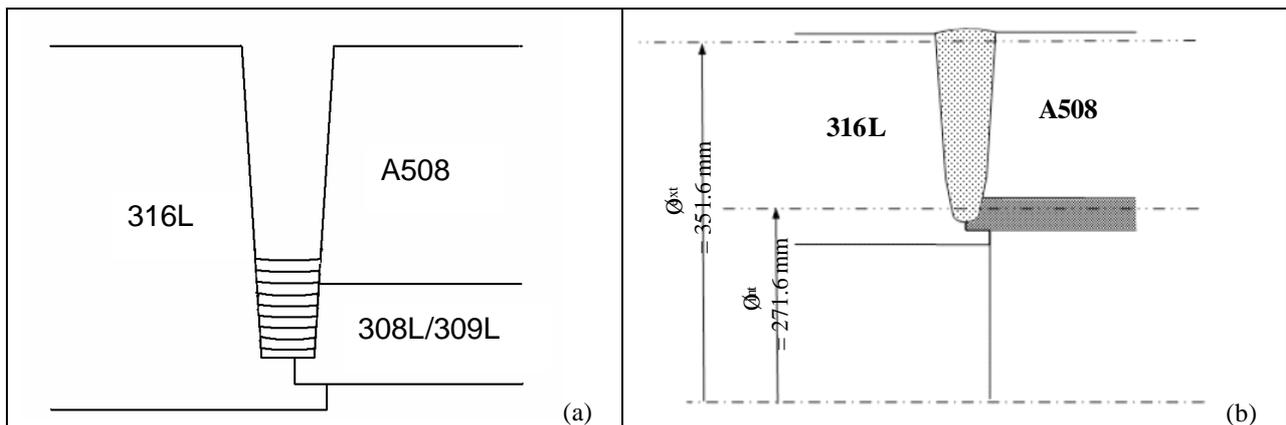
The 14" mock-up is an assembly of an A508 Class 3 ferritic pipe welded to a 316L austenitic pipe by means of an Alloy 52 Gas Tungsten Arc Welding (GTAW) narrow gap welding (see Fig. 1). Note also the presence of a weld-deposited cladding in 309L/308L austenitic steels (with coated electrode) on the ferritic edge.



**Figure 1.** Narrow gap dissimilar metal weld configuration

The main steps of the mock-up manufacturing procedure are (see Fig. 2):

- Weld-deposited cladding on the ferritic edge followed by a stress relief heat treatment,
- Machining of the two ends before narrow gap welding,
- Narrow gap welding with automatic GTAW process, 28 beads being deposited in the groove,
- Final machining of the mock-up,
- Post weld heat treatment.



**Figure 2.** Narrow gap welding sequence (a) and final machining of the 14" mock-up (b)

### 4 RESIDUAL STRESS MEASUREMENTS

Residual stress measurements have been carried out using two different techniques:

- Neutron Diffraction (ND) technique with the European Commission Joint Research Centre, Institute for Energy, in Petten, The Netherlands (Taylor et al. 2006),
- Deep Hole Drilling (DHD) technique with VEQTER in Bristol, UK (Ficquet et al. 2005).

Measurements have been performed throughout the thickness of the mock-up. Various locations from the weld centreline have been selected:

- The weld centreline,
- 9 mm from the weld centreline in the ferritic side,
- 9 mm from the weld centreline in the austenitic side.

For ND, sampling volume dimensions of  $7.5 \times 5.8 \times 25 \text{ mm}^3$  for the radial and axial directions and  $7.5 \times 5.8 \times 10 \text{ mm}^3$  for the hoop direction were chosen. Therefore the residual stresses were averaged over a volume which exceeds largely the Heat Affected Zone (HAZ).

For DHD, the 3 holes were drilled along radial lines located far away from each other, therefore there is no interference between measurements. This technique averages the residual stresses within its 5 mm diameter core for each measured point, hence reducing the gradient in the HAZ over this distance.

## 5 FINITE ELEMENT MODELLING

Meshing and calculations have been carried out using SYSWELD finite element (FE) code developed by ESI-Group (SYSTUS 2007). An approach similar to previous DMW computations has been applied (Courtin and Gilles 2006 and 2007). Considering 2D axisymmetric hypotheses, the analysis simulates each elementary step of the mock-up manufacturing procedure. Multipass welding simulation reproduces the deposit of each bead by thermo-metallurgical and mechanical calculations.

The main original points of the work are:

- The choice of non linear kinematic hardening models to describe material behaviours,
- The use of strain annealing and phase transformation techniques to reproduce physical process,
- The proposal of a simplified approach to model the cladding welding,
- The simulation of the PWHT by elasto-viscoplastic computations.

### 5.1 Material characteristics

The material values come from AREVA private database. Four materials are considered (see Fig. 1):

- A508 for ferritic base metal,
- 316L for austenitic base metal,
- 309L for austenitic cladding metal,
- Ni base alloy 52 for weld deposit.

Metallurgical transformations are simulated in the ferritic base metal whose various phases correspond to initial base metal, bainite, martensite, tempered ferrite and austenite. The basic characteristics values required for the thermal and mechanical calculations are: thermal conductivity, density, specific heat, Young's modulus, Poisson's ratio, thermal strain, yield stress, stress-strain curves to fit hardening model parameters. Note that the thermo-mechanical characteristics are required for each phase and should be given from the room temperature to the melting one, hence representing a large material database.

The materials are considered as homogeneous and their hardening behaviour is assumed:

- Isotropic for ferritic material,
- Non linear kinematic for austenitic ones,
- Mixing isotropic and non linear kinematic for Ni base alloy 52.

The plasticity criteria of the various hardening models are as follows (SYSTUS 2007):

- For the isotropic one,

$$F(\sigma_{ij}) = \sigma_{VM} - S_y \quad (1)$$

- For the non linear kinematic Armstrong-Frederick's one,

$$F(\dot{\sigma}_{ij}, \dot{\varepsilon}_{ij}^p) = \sqrt{\frac{3}{2}(\dot{\sigma}_{ij} - \dot{\varepsilon}_{ij}^p)^2} - S_y \quad \text{and} \quad \dot{\varepsilon}_{ij}^p = \frac{2}{3} c \dot{\sigma}_{ij}^p - \tilde{a} \sqrt{\frac{2}{3}(\dot{\sigma}_{ij}^p)^2} \dot{\varepsilon}_{ij}^p \quad (2)$$

Where:

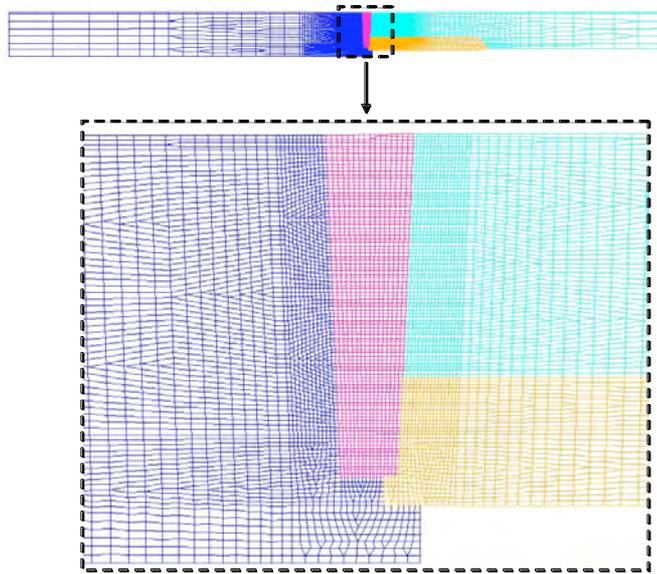
- F is the threshold function,
- $\sigma_{ij}$  and  $\varepsilon_{ij}^p$  are, respectively, the stress and plastic strain components,
- $\sigma_{VM}$  is the equivalent Von Mises stress,
- $S_y$  is the yield stress,
- $\chi_{ij}$ ,  $c$  and  $\gamma$  are non linear kinematic hardening model parameters.

To complete thermo-mechanical properties, several techniques have been used to well reproduce physical process:

- Strain annealing technique in austenitic metals and Ni base alloy,
- Dilution process of the A508 and 316L materials with the weld one,
- Elasto-viscoplastic computations for simulating PWHT.

## 5.2 Geometry and meshing

The dimensions are identical to the experimental mock-up ones. A unique model has been used for the whole welding procedure, i.e. for cladding, narrow gap welding, machining and PWHT. 2D axisymmetric assumptions could have been taken into account since only the residual stresses, and not the distortion, are relevant [for the present comparison](#) (Lindgren 2002). These hypotheses have been validated by many other studies in the past (Robin et al. 2002, Taylor et al. 2006, Courtin and Gilles 2006 and 2007). The model is meshed using linear elements and contains around 9 000 nodes. Meshing refinements particularly focused on the narrow gap and the HAZ, where each element is approximately a  $0.5 \times 0.5 \text{ mm}^2$  square (see Fig. 3).



**Figure 3.** Meshing refinements

## 5.3 Manufacturing process modelling

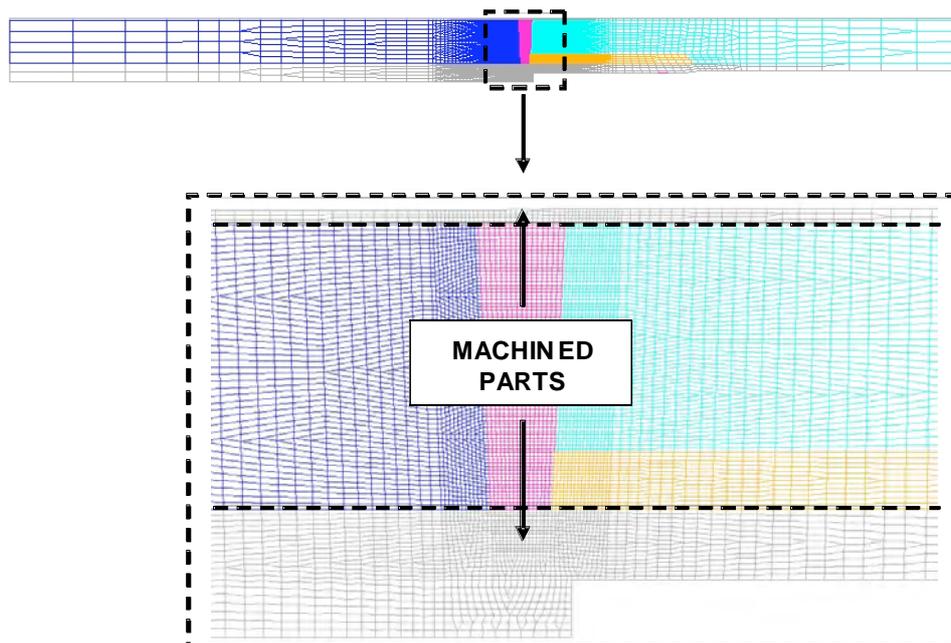
Multipass welding simulation (Taylor et al. 2006, Courtin and Gilles 2006 and 2007) has been used for GTAW narrow gap welding. The principle consists in identifying each pass in the meshing by grouping the elements and in activating them incrementally to simulate the deposit of each bead.

A preliminary specific work is necessary to obtain the thermal cycle similar to the welding operation one. Thermal FE computations with a cylindrical heat source, representing the torch, are required on a 3D model of the structure with a 360° weld bead. Adjustments of the heat source parameters are made to reach the melting temperature in the bead and to fit the experimental HAZ dimensions by iterative computations.

Since the main objective of this work is the narrow gap welding analysis and not the cladding one, the latter process has been simulated using a simplified approach. The weld-deposited cladding in 309L/308L on the ferritic edge being followed by a stress relief heat treatment, the cladding modelling has consisted here in simulating the final cooling of the piece during this heat treatment, by setting zero initial stress field values.

The machining step is simulated according to the manufacturing procedure (see Fig. 4). Modelling consists in making the element strength to vanish: the Young's modulus is decreased to a very low value and the Poisson's ratio is set to zero. Only the removal of material and its consequences on strain redistribution is taken into account. The heating due to machining is neglected. It is assumed that, except in a thin surface layer, the residual stress field due to welding is only modified by the strain redistribution induced by the removal of material and not by the surface heating during machining. This approach has already been validated (Taylor et al. 2006, Courtin and Gilles 2006 and 2007).

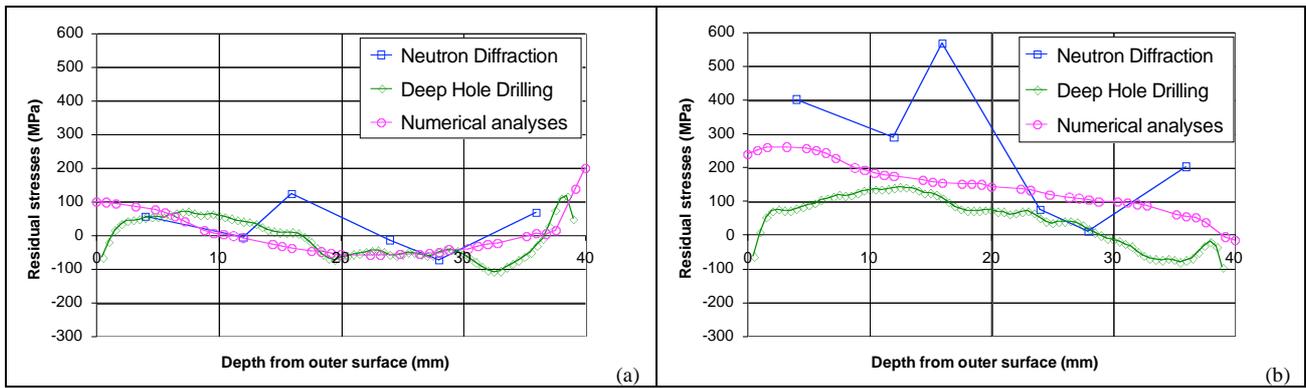
Last, as previously reported, PWHT has been simulated in the framework of these analyses. Elastoviscoplastic computations have been performed according to the PWHT description.



**Figure 4.** Machined parts

## 6 COMPARISONS BETWEEN MEASUREMENTS AND SIMULATION

As previously reported, various locations from the weld centreline have been selected for measurements. Fig. 5 illustrates comparisons between measurements and simulation at the weld centreline. Residual stress values are plotted as a function of the depth from the outer surface of the pipe.



**Figure 5.** Axial (a) and hoop (b) residual stresses at the weld centreline - Measurements and simulation

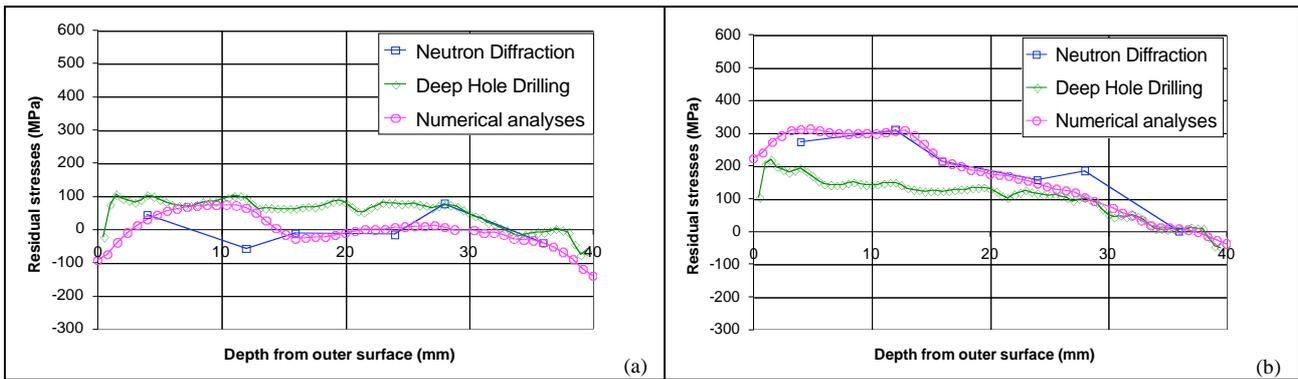
Numerical axial residual stresses at the weld centerline are in a very good agreement with measurements. Just slight differences may be noted close to the walls because machining effects are not taken into account in the simulation [and the selected measurement techniques are not suited to capture residual stress fields close to the surface](#). This phenomenon, already reported (Courtin and Gilles 2006 and 2007, Taylor et al. 2006), might be observed in the following comparisons.

[Machining effects induce residual stress over a distance of the order of 0.2 mm \(Valiorgue et al. 2008\), in any case much less than 0.5 mm. ND measurements cannot capture stress fields at a distance  \$d\$  from the surface less than half of a gage size: in the present case  \$d = 4\$  mm. DHD measurements are more likely to give the trend. The sharp decrease of stresses near the surface is consistent with the fact that turning induces compressive stress fields at the surface \(Valiorgue et al. 2008\).](#)

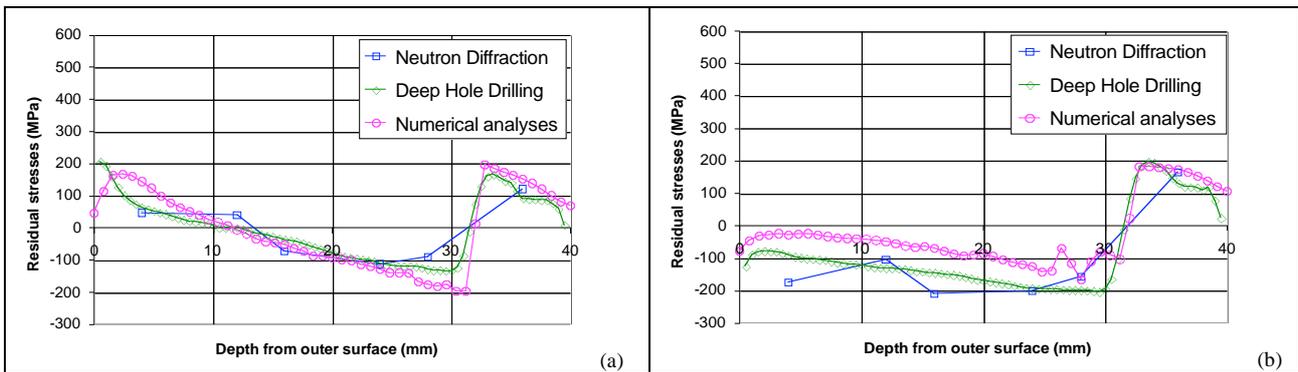
Concerning the hoop residual stress field at the weld centerline, large differences can be found between ND and DHD measurements. In this case, numerical results may be considered as satisfactory. Note that [uncertainties in ND method are much higher for thick components \( \$> 30\$  mm\) and the maximum of the error is close to the mid-thickness \(Goudar et al. 2008\). On the other hand DHD method seems to underestimate hoop stresses close to the outer wall in circumferential welds \(Ogawa et al. 2008, Kingston et al. 2008\).](#) Lastly, [the numerical assumption of axisymmetry leads usually to an overestimation of the hoop stresses close to the outer wall, provided there is no stop and start weld effect \(Brust and Rudland 2008\). Except for some out-of-scale values, the agreement on hoop stresses should be expected to be better between computed and ND values.](#)

Fig. 6 shows comparisons at 9 mm from the weld centreline in the austenite side. Again, numerical results are in good agreement with measurements. However, it can be seen that they are sometimes closer to ND measurements and sometimes to DHD ones.

Fig. 7 shows comparisons at 9 mm from the weld centreline in the ferritic end. Numerical results are in a very good agreement with both ND and DHD measurements. The 309L cladding impact has been well caught. Note that numerical compressive hoop residual stresses in the ferrite side are slightly lower than measurement ones.



**Figure 6.** Axial (a) and hoop (b) residual stresses at 9 mm from the centreline in the austenite side - Measurements and simulation



**Figure 7.** Axial (a) and hoop (b) residual stresses at 9 mm from the centreline in the ferrite side - Measurements and simulation

To conclude, it can be highlighted that the present complex numerical welding simulation has proved to be very efficient. Simulation results are in good agreement with measurements:

- For axial and hoop residual stress fields,
- At the weld centerline, in the 316L side, in the A508 side and in the cladding.

Numerical predictions for axial stress fields are in better agreement with both ND and DHD measurement techniques. For the hoop stresses, the values are sometimes closer to the ND measurements but may be overestimated on the outer surface as a result of the axisymmetry assumption. Nevertheless, keep in mind that possible differences between ND and DHD measurements illustrate the difficulty of these experimental techniques.

Note also that sensitivity analyses have pointed out the necessary character of taking into account non linear kinematic hardening behaviours and strain annealing, and modelling machining and PWHT.

## 7 CONCLUSION

This paper has presented computations performed by AREVA NP on a 14" narrow gap DMW configuration. Considering 2D axisymmetric hypotheses, the analysis simulates each elementary step of the mock-up manufacturing procedure. Multipass welding simulation reproduces the deposit of each bead by thermo-metallurgical and mechanical calculations. The main original points of the work are:

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- The PWHT simulation by elasto-viscoplastic computations.

For validation, the numerical results have been compared to measurements obtained by two different ways: neutron diffraction and deep hole drilling techniques. The residual stress fields have been observed at

various locations from the weld centreline, in the depth of the pipe. The numerical results are in a very good agreement with measurements and they totally catch the trend of the residual stress fields.

Within the framework of narrow gap DMW configurations, this work gives another evidence of the relevance of the numerical welding simulation to predict residual stress fields in welded components and highlights the capability for AREVA NP to perform, with success, such a kind of analyses. Note that this paper gives also some elements to have a look on the validity of both numerical and experimental techniques.

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