Framatome-ANP Experience in Numerical Simulation of Welding

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ABSTRACT. For nuclear reactor manufacturers, ensuring a high quality of welded joints is one of the basic design rules. Qualification of welders, specific procedures, stress relief heat treatments serve efficiently this goal. Numerical simulation of welding adds the capability of assessing residual stresses, distortions, and in a near future quality of welds. Since almost 25 years, Framatome-ANP has been working on numerical simulation of welding to improve predictions and efficiency of computational tools, namely using the worldwide known SYSWELD®. The largest part of Framatome-ANP experience in this field relies in the numerous studies performed by German and French teams on industrial components. This paper tries to account for all these efforts, following a presentation oriented on types of problem.

RÉSUMÉ. Pour les constructeurs de réacteurs nucléaires, assurer une haute qualité aux joints soudés est une des règles fondamentales de conception. La qualification des soudeurs, les procédures spécifiques, les traitements thermiques de détensionnement servent cet objectif. La simulation numérique du soudage offre la possibilité supplémentaire d'évaluer les contraintes résiduelles, les distorsions et dans un futur proche, la qualité des soudures. Depuis près de vingt-cinq ans, Framatome-ANP travaille à maîtriser la simulation numérique du soudage, notamment avec le logiciel SYSWELD® de réputation mondiale. La plus grande part de l'expérience de Framatome-ANP dans ce domaine est constituée de toutes les études réalisées par les équipes allemandes et françaises sur des composants industriels. Cet article rend compte de tous ces efforts en suivant une présentation par type de problème.

KEYWORDS: pressurized water reactor (PWR), welding, numerical simulation, residual stresses, distortions, welding process.

MOTS-CLÉS : réacteurs à eau pressurisée (REP), soudage, simulation numérique, contraintes résiduelles, distorsions, procédé de soudage.

1. Introduction

No large structures without welds, but the welding process has to be carefully managed to avoid defects. Welding of components is not straightforward for the following reasons:

– Risk of cracking by incomplete fusion, homogeneity defect, cold cracking;

– Manufacturing difficulties: a minimum heat input is required for metal melting, but a strict control of heating and cooling speed is necessary: high speed to avoid hydrogen trapping and large Heat Affected Zone, but no overheating to avoid large grains. Requirements on chemical composition of welding material have to be followed strictly for ensuring a good mechanical strength of the joint and controlling the shape of beads. On thin structures, the welding sequence may influence the distortions of welded parts.

– Creation of residual stress fields which strongly impact some types of damage, specifically crack initiation and propagation due to fatigue or/and corrosion. Such stresses are generated during fabrication and are sometimes difficult to eliminate.

These are some of the reasons why welding procedures are carefully tested and Post Weld Heat Treatments are applied for reducing residual stresses in welded joints. For all of these problems, numerical simulation of welding may be of a great help, however the R&D effort to achieve good predictions depends a lot on the considered case and the targeted objective. For example, the case of a ferritic weld is more complex than the case of an austenitic stainless steel weld used in Pressurized Water Reactors (PWR), because in the latter, no phase transformation occurs during welding (except strain recovery at high temperatures) and therefore no additional strains due to the phase transformation have to be considered. In a general way, one may rank the welding problems in an increasing order of difficulties as follows: residual stress prediction, distortion assessment, checking the welding process effectiveness, defect appearance prediction. Depending on the objectives, the information required and the models may be different.

Residual stresses present in Pressurized Water Reactors do not constitute a major problem at the design stage. They do, however, strongly impact some types of damage – specifically fatigue crack and corrosion crack initiation (Fricke *et al.*, 1998; Gilles, 2002). However welding stress relief is not always efficient (impossible in case of bi-metallic welds) and their trough-thickness measurement is almost impossible on-site. Numerical simulation of the welding process is in most of the cases the only way to obtain residual stress fields and therefore improve the accuracy of defect assessments.

The finalization of welding process could be improved or made less expensive if numerical simulations are used to fix the optimum values of welding parameters. Prediction of potential welding induced damage is under investigation.

This explains why Framatome-ANP is spending large R&D efforts in welding stress simulation since 25 years (Pellissier-Tanon and Bergheau, 1992). Quite a lot of these actions have been done in partnership with ESI-group, who is now developing SYSWELD® (SYSWELD, 2003), the Framatome-ANP created software dedicated to temperature and stress field computation during welding or other heat treatments involving interactions between thermodynamics, metallurgy and mechanics. Now the problem of residual welding stress assessment is well mastered. Progress in know-how have to be made, namely in the determination of the Heat Affected Zone and weld metallurgical structures, heat input modelling, interactions between welded joint and structure and also in the reliability of measurements to which computations are compared for validation purposes.

One of the key factors of scientific development is to re-examine forces and weaknesses of the past studies. This paper aims to contribute to this task.

2. From SYSWELD® origin to Framatome & Siemens fusion

Both companies Siemens, through KWU-AG, and Framatome were very successful in manufacturing nuclear plants and selling services, when they decided in year 2000 to merge into Framatome-ANP (Advanced Nuclear Power). Both had a large experience in welding, but also in welding simulation. The evolution of SYSWELD® code dedicated to welding and used by Framatome-ANP France, now developed by ESI-Group, gives a good picture of the R&D efforts made by Framatome-ANP to succeed in welding simulation. The Siemens/KWU (now Framatome-ANP GmbH) welding simulation team is using for their numerical investigations the commercial finite element code ABAQUS with some own material routines. The cumulative experience of German and French teams in residual stress and distortion computations is quite consistent as shown in § 2.2 and 2.3.

2.1. *SYSWELD® story*

In 1979, Framatome-ANP created SYSWELD®, one of the first Finite Element software dedicated to welding simulation. The main objective at that time was to take into account, in thermo-mechanical computations, the effect of phase transformations occurring during the welding of the pressure vessel ferritic steel. The mains steps of SYSWELD® evolution are listed below.

– Creation in 1979

– 1982: SYSWELD® becomes an operational software

  - Hydrogen diffusion model

  - Phenomenological model for metallurgical transformations (Leblond and Devaux, 1984)

  - Plastic behaviour of steels during phase transformations (Leblond *et al.*, 1986, 1989)

– 1988-1995
- New model of phase transformations
- Formulation in the heat source commoving frame (Bergheau *et al.*,1992)
- Coupling between electromagnetism and metallurgy
- Resistance spot welding simulation (Robin *et al*., 2002)
- Radiation in cavities (Bergheau and Potier, 2001)
- Activation/deactivation of elements

– 1995-2000 (Boitout *et al.*, 1997)
- Modelling of aluminium alloys
- Pre-programmed heat sources
- Moving refinement procedure (see § 4.3.)

– Beyond 2000
- New data processing
- Viscoplasticity (Vincent *et al.*, 2003)
- Local/Global methodology (see § 4.3.)
- Welding of shells.(Faure *et al.*, 2004) …

2.2. *French team studies*

The studies conducted by Framatome-ANP have been mostly devoted to Pressure Vessel (ferritic steel cladded with stainless steel) and Dissimilar Material Weld. However the thermomechanical behaviour of stainless steel components during welding has been also analyzed for validation purpose. The different type of studies may be listed as follows:

– Validation of SYSWELD®, analytical studies on cold cracking and hydrogen diffusion (Dubois *et al.* 1985, Leblond *et al.*, 1987, Boitout 1997);

– Computation of underclad residual stresses in the Pressure Vessel accounting for phase transformations in the base metal (See § 5.1.);

– Analysis of weld repairs (Devaux J. *et al.*, 1991, Monnot *et al.*, 1992);

– Simulation of butt TIG welding of stainless steel thick pipes (Chabenat *et al.*, 1992);

– Simulation of elasto-viscoplastic behaviour of steels during phase transformations (Bergheau *et al.*, 2002);

– Simulation of butt TIG welding of stainless steel thick pipes (Razakanaivo *et al.*, 2001);

– Simulation of weld material deposit on a stainless steel plate (IIW benchmark, Depradeux and Jullien, 2004);

– Simulation of the International Thermonuclear Experimental Reactor (ITER) Vacuum Vessel distortions (See § 4.3.);

– Dissimilar Material Weld (DMW) studies:

- Pressurizer and pressure vessel nozzles

- DMW pipe junctions of the BIMET and ADIMEW EC projects (Devaux J. *et al.*, 2000; See § 5.2.).

2.3. *KWU & Framatome-ANP GmbH experience*

– Analysis of welding of an austenitic pipe (Engelhard *et al.*, 1998)

– 1997: Project "VORSAC" (EC): Variation of Residual Stresses in Aged Components; Numerical and experimental investigations on austenitic piping

– Project "PHARE" (EC) 1997: Residual stress calculations for repair welds of sub-clad defects on a VVER reactor (Russian version of PWR) (PHARE 97) using Inconel 52

– 1998: 3D welding simulation of two austenitic pipes (Engelhard *et al.*, 1998)

– 2000: Effect of last pass heat sink welding and service transients on residual stresses (Keim *et al.*, 2000), numerical and experimental residual stress investigations

– 2001: Numerical simulation of the welding process of a BWR pump nozzle (Keim and Palagyi, 2001)

– >2002: Project "ENPOWER" (EC). Weld repair in a cladded ferritic plate simulating deep and shallow grooves and repaired with austenitic or cladded ferritic filler material; numerical and experimental residual stress investigations

– 2003: NESC III: Weld simulation of the ADIMEW dissimilar weld.

3. *V*alidation of models

In absence of phase transformation, any reliable thermo-mechanical software may be used for welding simulation. Framatome-ANP uses ABAQUS® (ABAQUS, 2001) and SYSTUS® (SYSTUS, 2003) for such types of studies like welding simulation of austenitic stainless steels.

When physical phenomena involves a significant coupling between heat transfer, metallurgy and mechanics, as it is the case for welding of ferritic steels (fig. 1), then specific mathematical models describing these couplings have to be developed and special modules implemented in the software. The validation of these models is a heavy task since requiring material characterisation up to high temperatures for each phase. The next paragraph gives a word on models implemented in SYSWELD® and describes shortly the model used for welding simulation of ferritic steels. The following paragraph shows the work completed with INSA-Lyon and other French partners (EDF, BCCN) to achieve a systematic validation of welding simulation of the 16MND5 (AISI A508) steel and of Z2CND1712 (AISI 316L) steel, considering hardness recovery. This work ended up with an enrichment of the Leblond model and the constitution of a proprietary data base gathering all material characteristics, parameter values to be used in the models and validation tests.

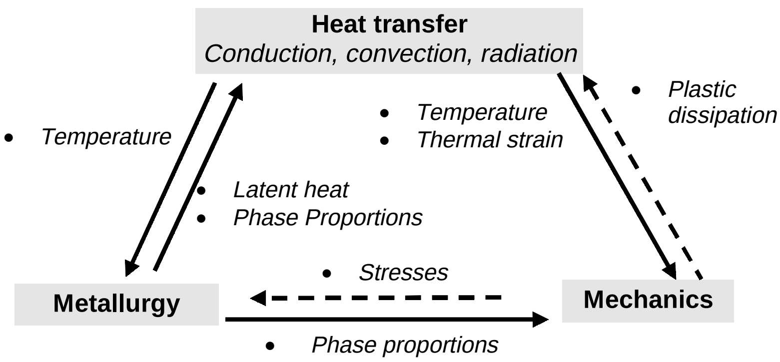


Figure 1. *Interactions of physical phenomena in the solid during welding*

3.1. *The Leblond model & other SYSWELD® models*

SYSWELD® allows simulating several manufacturing processes such as welding, quenching, induction and case hardening, hydrogen diffusion (Bergheau and Leblond, 1990). Several models are available to describe welding of steels and aluminium alloys. Thermal properties can be phase and temperature dependent. SYSWELD® also simulates radiation phenomena, like those appearing in a furnace heat treatment.

SYSWELD® accounts for three types of thermo-metallurgical interactions: thermal history effects on phase transformations, latent heat effects and phase-dependent thermo-physical properties. The code offers two models to describe transformation kinetics in materials (Leblond *et al.*, 1984, Denis *et al.*, 1992, Pont *et al.*, 1994). For steels, these models are suited to reproduce the Johnson-Mehl-Avrami law describing phase transformation with diffusion and the Koistinen-Marburger law for Martensite transformations.

Framatome-ANP engaged in the early eighties an intensive work on modelling the mechanics of phase transformations in ferritic steels on the basis of the studies conducted in the LSGMM laboratory in Nancy (Abrassart, 1972). Then a fruitful partnership between the team conducted by J. C. Devaux and J. B. Leblond produced a model accounting for the changes in plastic behaviour (fig. 2) induced by the structural transformations of the ferritic steel under thermo-mechanical loading.

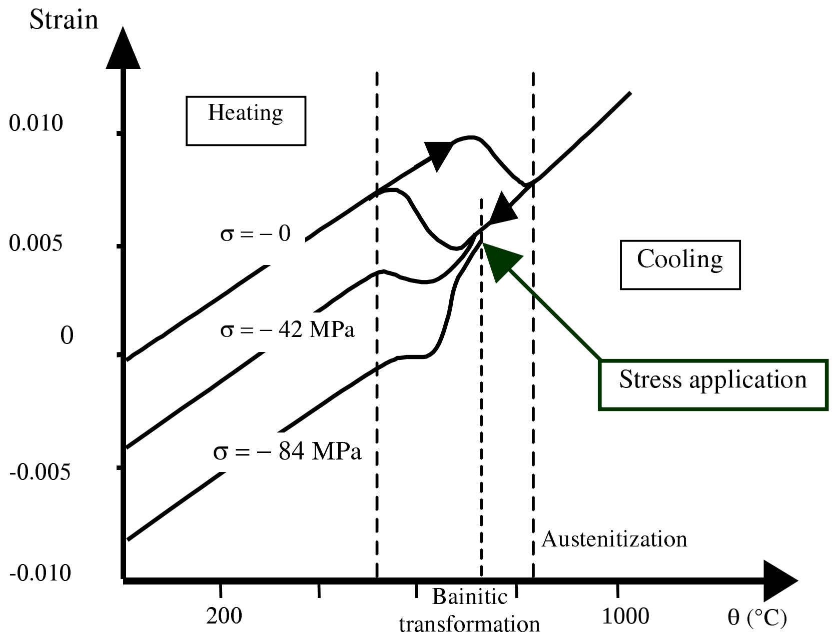


Figure 2. *Combined dilatometry test*

The model developed by Leblond and co-workers (Leblond *et al.*, 1986, 1989, Leblond, 1989) is a refined extension of the Greenwood and Johnson model (Greenwood and Johnson, 1965). The model is based on a micromechanical analysis relating transformation plasticity to ordinary plasticity. Leblond has proven that a structural transformation adds to the total macroscopic plastic strain a term, the time derivative of which is proportional to the derivative of the volume proportion of the created phase. The demonstration is based on a homogenization method and hypotheses suited to isotropic materials. The applicability of the derived formulae to the behaviour of ferritic steels has been carefully checked through numerical simulations on elementary structures and theoretical studies on totally plastic individual phases. This model appears to be attractive for practical applications since requiring only the knowledge of usual thermo-mechanical parameters: no coefficient has to be fitted on transformation plasticity experiments for the considered material. The model accounts also for hardening and recovery effects.

More recently, viscoplasticity of phases has been taken into account in the Leblond model (Vincent *et al.*, 2003). This extension has been shown very efficient for modelling the behaviour of thin structures subjected to high temperature variations.

3.2. *The INSA-LYON systematic validation studies*

EDF, BCCN (French Safety Authorities) and Framatome-ANP are developing with the INSA-Lyon laboratory a long term partnership, in perspective of welding simulation model, tool, data base development and validation. Models are implemented in SYSWELD® or the EDF code ASTER® and simulations are compared to tests of increasing complexity performed in INSA-Lyon or other laboratories. Three steps are usually followed in the validation approach:

– analytical tests for improvement and validation of constitutive equations;

– validation tests on mock-ups for detailed checks of the model on simple structures;

– tests on structures: closer to a real welding operation.

The analytical tests are 1D tests providing homogeneous fields of temperature and stress. These are "Satoh" type of tests (Satoh a, b, 1972) performed on homogeneously heated tubes, the axial displacement of which is restrained (fig. 3).

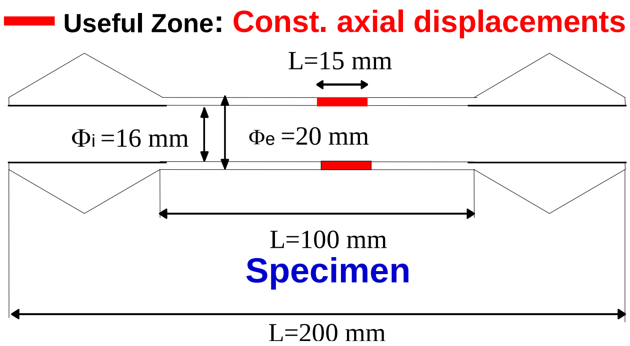


Figure 3. *Scheme of the Satoh specimen, homogeneously heated under zero strain*

Observations are made in a central part of the tube (operating section) where temperature and stress fields are homogeneous. Since the overall strain is prescribed to be zero throughout the thermal cycle, an axial stress develops. At all points of that operating section, physical phenomena occur simultaneously under a uniform axial stress field. The stress measurements give the stress related to transformation plasticity or strain hardening changes. A special dilatometer (Cavallo *et al.*, 1999) dedicated to these thermo-mechanical tests has been set up. The tubes are heated by Joule effect and for high cooling rates was forced by a flow of nitrogen. The device allows reaching a temperature greater than 1,100°C at rates close to 100°C/s. An example of test which illustrates the effect of transformation plasticity is presented in fig. 4. More details on the device and a full application of the test procedure are explained by Vincent *et al.* (2004). Mechanical uniaxial tensile tests were also performed at different strain rates.

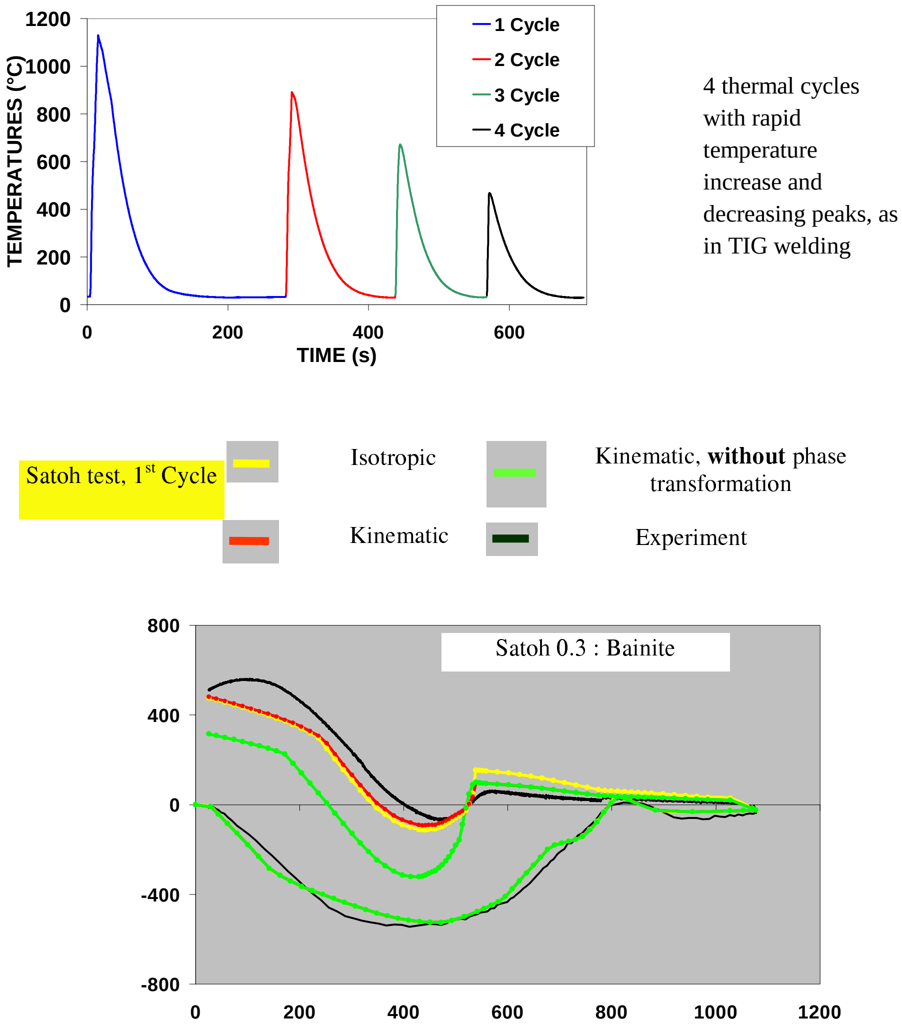


Figure 4. *Influence of transformation plasticity on stress-temperature variations*

The basic validation tests have been carried out on discs heated by a LASER beam. The LASER beam rotates to ensure the axisymmetry of the system. The objective of developing such a device was to analyze the effects of gradients of temperature and stresses. The temperature is limited so that no fusion occurs except in a very recent test. The other limitations of the test are the absence of welding material input and the fixed position of the heat source.

Test programs on thin and thick discs were designed in such a way that all thermal, metallurgical and mechanical phenomena occurring in the Heat Affected Zone during a welding operation would be present. Several examples of results obtained on this device are illustrated. Fig. 5 shows a good agreement between the measured and computed HAZ in a ferritic thick disc. The need of a viscoplastic model for representing the evolution of mechanical properties in a HAZ has been proven for thin ferritic discs (Bergheau *et al.,* 2004). Fig. 6 exhibits excellent comparisons between measured and computed displacement as well as residual stresses for austenitic discs (Depradeux and Jullien, 2004).

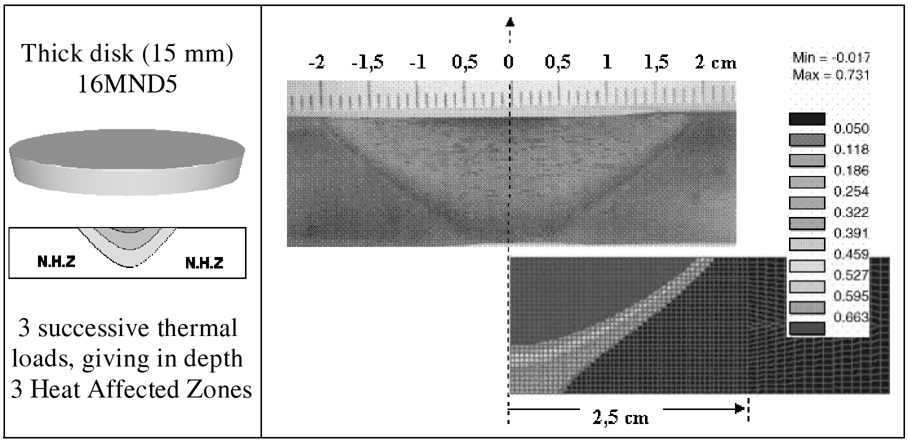


Figure 5. *Comparison of measured and computed Heat Affected Zones in a disk*

Up to now, studies were carried out on a 16MND5 low-alloy carbon manganese steel (Grostabussiat 2001, Vincent *et al.,* 2002, 2004) and on a Z2CND17-12 (Depradeux and Jullien, 2003) austenitic stainless steel. These steels are respectively used in the manufacturing of pressurized water reactor vessels (PWR) and of pipes for French nuclear power plants. For the ferritic steel, models representing phase transformations, plasticity and viscoplasticity of phases have been carefully finalized and checked using the two first type of tests. For the Z2CND17-12 steel, the strain recovery effect was also taken into account as well as the viscoplastic behaviour.

All the material characteristics and parameters used for the simulations, as well as test results have been stored in a data bank called BIFE (from the initials of the partners).

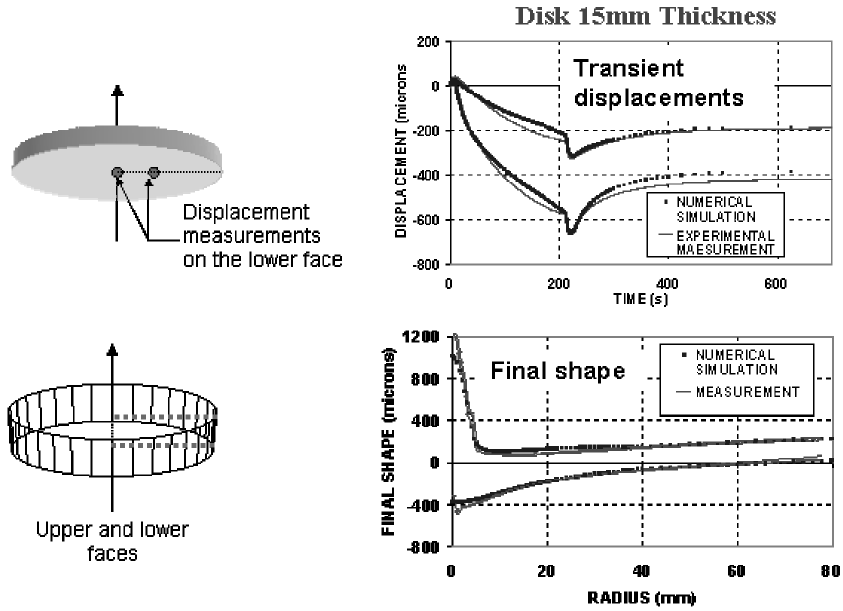


Figure 6. *Comparison of measured and computed shapes of 316L disk*

4. Modelling and validation of multipass welding

The simulation of multipass welding is a challenge for PWR since most of the pressurized components are very thick and some of them are joined with bi-metallic welds. Two complementary ways have been explored by Framatome-ANP in this field:

– development of simplified approaches for specific cases, requiring validation studies;

– direct computation of all the passes and development of tools reducing the time spent in modelling the weld and data preparation.

4.1. *Research of simplified approaches*

The pressure in the primary loop of PWR plants reaches 21 MPa in the hydrostatic test; therefore large pipes are very thick. In the 16" Dissimilar Metal Weld in the surge line of the French N4 reactor, more than 90 passes are piled up and the buttering contains 70 passes. Simulation of such a weld manufacturing may be simplified in several ways:

– If the geometry is axisymmetric as for a girth weld, then the problem may be treated as an axisymmetric one, the self restraint due to parts remaining cold during welding being taken into account by appropriate boundary conditions: fixed end displacement is applied during the heating phase and free boundary conditions during the cooling phase.

– The macrobead technique which consists in substituting one bead to a group of beads. The macrobead is an envelope bead with an equivalent thermal cycle giving rise in the adjacent to the base material. This will be illustrated in § 4.2.

– During the stationary phase of welding, mechanical calculations may be conducted in 3D using a moving frame technique, but on plates for one pass only.

– Another way of simplification is the reduction of the time steps of the mechanical computation. The key time steps correspond to an evolution of the temperature gradients which induces a significant change of stress distribution in the structure. The instant corresponding to the full yield of the thickness is one of these key time steps. This approach has been explored by CEA, but it seems difficult to apply in 3D cases.

All of these simplifications are limited to simple structures like plates and pipes and require a good experience for judging of their applicability. In any case, we will not recommend any simplification when computing temperatures: the 3D thermal computation is not so costly.

4.2. *Development and validation of the macrobead technique*

4.2.1. *The macrobead technique*

Satoh tests on austenitic stainless steel have shown that after successive heating-cooling cycles, the stress at room temperature is driven by the maximum temperature and almost independent of the following cycles with lower maximum temperatures. Hardening effect due to cycling was observed in compression during the heating phase, not in the cooling phase. This may be due to hardening restoration effects. Therefore, only cycles of maximum temperature have to be known, i.e. fusion temperature cycle in the melted zone and in the HAZ, the cycle corresponding to the nearest bead deposit. Information about cycles due to one adjacent deposit is also of interest. For a multipass weld, deposits will be grouped in layers and cycles corresponding to the deposit of one bead will be applied to the layer in such a way that the thermal gradients in the neighbouring material will be the same as after deposit of all the beads of the layer. The only difference with a full layer deposit simulation is that the layers are deposited at the same time in the macrobead technique.

This approach do not give correct cumulative strains, it should not be used for predicting displacements. The application of this method requires computing the thermal history of one bead deposit. The validation of this technique has been performed by comparing to a reference test on a mock-up presented below.

4.2.2. *Reference test and analyses*

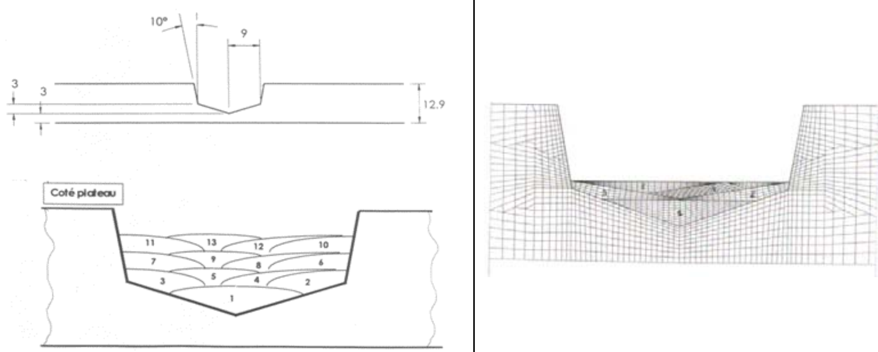
Framatome-ANP conducted in cooperation with CEA and EDF a validation study of butt welding simulation of two austenitic 316L cylinders (Razakanaivo *et al*, 2000). The basis of the action (which will be referenced as A13pipe) was the manufacturing of an instrumented mock-up by Framatome-ANP. External diameter was 220 mm, thickness 12.9 mm and total length 560 mm. The structure was maintained horizontal and clamped at one end to a rotating plate, the other end being free. These boundary conditions induced a dissymmetry of residual stresses on the outer wall, mainly on the circumferential stress which has much higher values on the plate side.

In the centred single-vee groove, thirteen weld beads have been deposited by TIG process (fig. 7). Thermal transient and displacements were registered all along the welding. Thermocouples were fixed at about 1 and 3 mm from the groove edge. Residual stresses were measured on outer surface along three meridian lines, using X-ray and Hole Drilling techniques. These measurements were performed at room temperature after the 5th, 9th and 13th passes. A preliminary mock-up welded with 13 interrupted passes was manufactured taking several cross sectional micrographics for obtaining indications on the bead shapes.

MAQUETTE TIG INSTRUMENTÉE

GÉOMÉTRIE

MAILLAGE



Dimensions du tube :

- Diamètre extérieur : 220 mm
- Epaisseur : 12,9 mm
- Longueur totale : 560 mm

Figure 7. *Scheme and mesh of the welding beads in the A13pipe mock-up*

Then, the three partners supporting this action performed 2D-axisymmetrical numerical simulations of the process and results were compared with experimental data (displacement and residual stress measurements were made at 3 different azimuths around the circumference). Differences between calculations come essentially from the modelling of the beads and the tensile stress-strain curve representation. Isotropic hardening was assumed. Three different meshing of the beads were considered. One of the important results of this action is that there is no need to represent the exact shape of the beads, provided the measured cross section area of each deposited bead is kept and adjustment of the heat input has been done on a similar mesh. A Gaussian power density is used in order to obtain a better description of the molten zone. The heat input is calibrated on the melted zone and the temperature distributions measured close to the weld. The mechanical computation was conducted in large deformations.

In spite of experimental scatter (the initial stress state has not been measured), computed axial residual stress distribution exhibit a good agreement with the Hole Drilling measurements in the welded zone. The hoop stresses on the plateau side are overestimated in the weld. The groove shrink values measured at different angles in the cross sections are very close to each other: this validates the axisymmetry assumption. The computed shrink (fig. 8) is in good agreement with these results because between each pass sufficient cooling time has been considered.

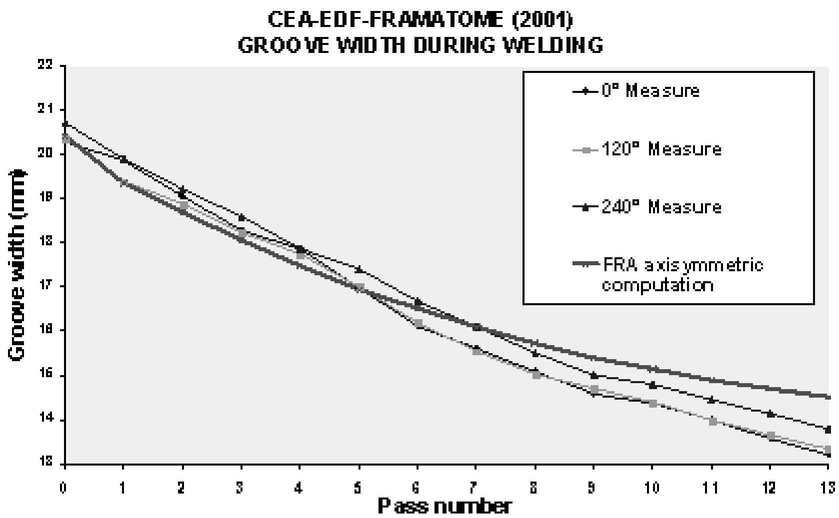


Figure 8. *Measured and computed groove shrink during welding*

4.2.3. *Comparison with a macrobead simulation*

The macrobead technique has been applied to the above described configuration A13pipe. The same hypothesis as in the axisymmetric computations made for the full simulation of the 13 pass deposits were considered for the macrobead computations. A sensitivity analysis was made on the waiting time between passes, since the macrobead technique assumes a return to ambient temperature between each passes. The difference on residual stress value was not significant. Residual stresses may be influenced by the interpass temperature, but strain recovery effects seem to reduce the importance of this effect.

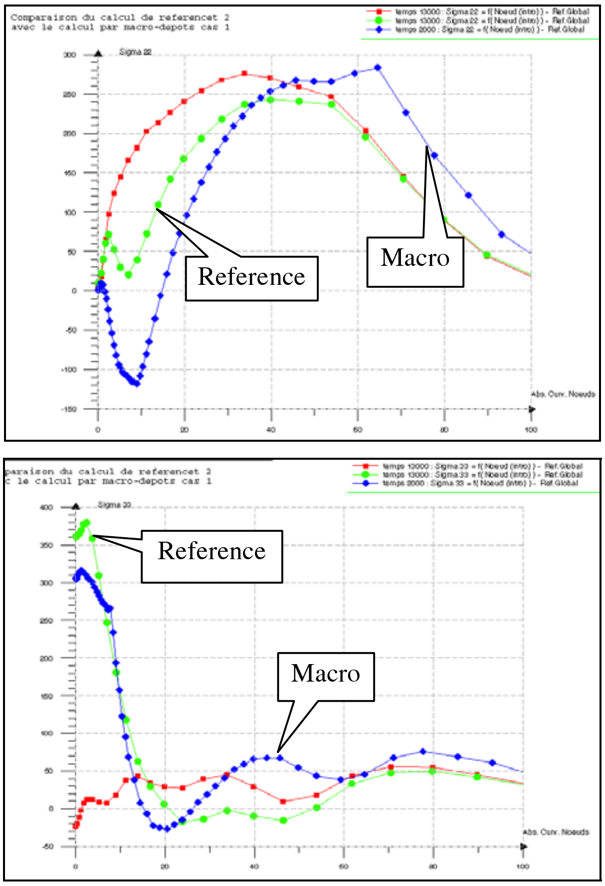


Figure 9. *Validation of the macrobead technique: comparison of stresses on the outer pipe wall*

The residual stresses obtained with the macrobead technique do not exhibit any dissymmetry since sequence effects are not considered. The technique gives results close to the maximum stress values obtained in the full pass deposit simulation on the plate side (fig. 9). The shrink of the groove is underestimated.

4.3. *Three dimensional numerical simulation of multipass welding*

3D simulation of multipass welding remains still costly, but in many cases of multipass welding no 2D simplifications can be made. Framatome-ANP has conducted several studies in 3D and developed with ESI tools for reducing mesh size and computational time.

4.3.1. *The moving refinement technique*

During welding, the extremely high temperature gradients around the heat source induce high stress values and gradients locally yielding the structure. This heat source is moving and the mesh must be refined all along the welding path leading in 3D computations to very large finite element models. To reduce the number of elements of the model and shorten computation times an adaptive meshing procedure has been implemented in SYSWELD®.

The principle of the moving refinement technique (Duranton *et al.*, 2004) to the welding simulation of a structure consists in using a local refined mesh where the temperature cycle is applied and moving this local mesh on a coarse mesh representative of the global stiffness of the structure along the welding path. This methodology significantly downsizes the meshes, while ensuring model consistency. The “moving refinement” associates an adaptive meshing procedure to a physical quantity transfer method from a refined mesh toward another one to carry out a full simulation of the process as illustrated in fig. 10. In the present study the data transfer method used consists in transferring the physical quantities directly from and to Gauss points.

This technique has been applied to the pipe butt welding A13pipe. A 3D step by step simulation of the five first weld passes is performed using the moving refinement procedure. The refined area is defined within an angle of 60°. The refined zone is moving by a rotation of 9°. Forty refined meshes are needed for one pass. Ten time steps are done on the same mesh. The initial mesh contains 28,000 nodes and 26,000 elements. The refining procedure leads to a 56,500 node and 81,000 element mesh. The simulation of the same process has been achieved in 2D to compare the real structure welding condition in 3D and the simplified approach in 2D. Indeed, two-dimensional models of tubular structures generally give rather satisfying results (see § 4.2). However, only 3D analyses are liable to produce results on restart conditions and on non complex shaped structures. The mechanical computation is realized using a small strain and small displacement formulation. As the pipe is not clamped during welding, no boundary conditions except those to prevent rigid body motion are applied. Relative displacement between the top edges of the chamfer was measured after each pass. Comparison with simulation shows a good agreement (Duranton *et al.* 2004).

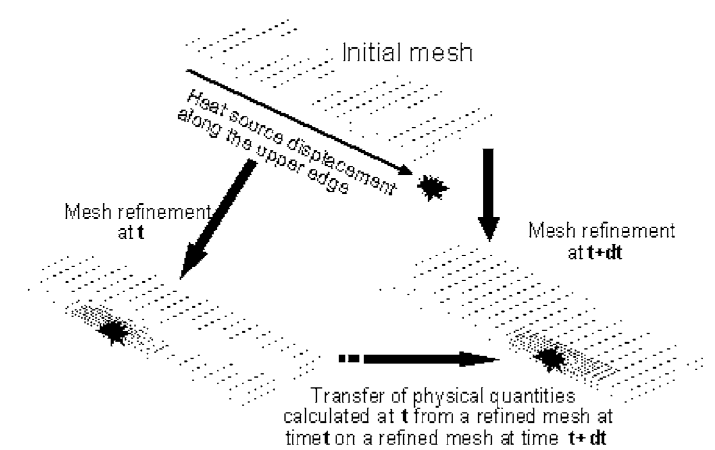


Figure 10. *Moving mesh refinement (from Duranton* et al., *2004)*

Comparisons between measured and calculated hoop and axial stresses on the external surface are given in fig. 11. For axial stresses, the comparison is quite good until 20 mm from the middle of the groove. Beyond this distance, the 2D analysis strongly overestimates the hoop stresses. Outside this large difference the results are quite close between 2D and 3D modelling, although 2D assumptions cannot reproduce the higher stress values that can be observed in the overlapping regions.

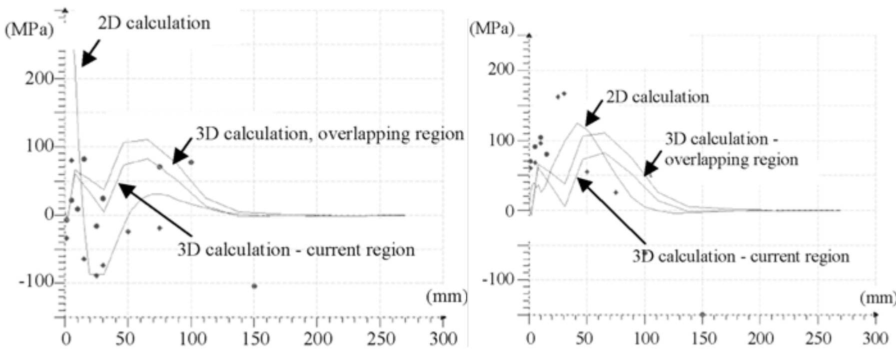


Figure 11. *Hoop (left) and axial (right) stresses on the external pipe surface (from Duranton* et al. *2004)*

The use of an adaptive meshing procedure reduces CPU costs by a factor of five. Furthermore, comparison with measurement gives satisfaction on displacement results, but to a lesser extent on residual stresses for which measurements is difficult to compare due to some residual stresses coming from manufacturing of the pipes before welding. The present software brings deep insight into the effect of pass overlapping and ovalization as it considers proper boundary conditions such as the bead retrain due to successive material deposits.

4.3.2. *Some 3D welding simulations*

Prediction of residual stresses in a BWR TIG welded pipe (LPHSW)

An example of a 3D computation of an austentic stainless steel weld in a Boiling Water Reactor (BWR) plant is given, (Keim *et al.*, 2000). Background is that intergranular corrosion attack of stainless steel piping in BWR plants is concentrated in an area immediately adjacent to the fusion line of the weld root. A remarkable feature is the synergistic occurrence of such defects in association with contraction folds.

Residual stresses are thought to trigger InterGranular Stress Corrosion Cracking (IGSCC). Many different measurement methods have therefore been used to determine residual stresses both in representative new welds and in weldments (circumferential pipe welds) which are already in service. However, a disadvantage common to all of these measurement methods to a greater or lesser degree, is that they integrate the results over a specific measurement length and therefore yield only an approximation of the actual value measured in the component only a short distance away from the fusion line. Tolerances, whether dimensional (root dimensions) or those associated with welding parameters, which unavoidably affect the component during fabrication, and tolerances inherent to the measurement technique tend to produce results with wide-ranging tolerance limits. Numerous measurements must be performed to express these limits in a tangible and acceptable form, and this, in turn, demands complex and costly experimental procedures. This latter consideration is an important starting point for applying numerical simulation to obtain quasi-neutral results with defined boundary conditions while also allowing parameters to be varied without the need for expensive experimental work.

The experimental part of the work consisted mainly of two steps:

– welding of an austenitic pipe by manual arc weld (TIG process) with an additional Last Pass Heat Sink Weld (LPHSW = welding of a last pass on the outer surface during simultaneous cooling of the inner surface with water) to improve the stresses at the inner surface;

– after welding loading of pipe by pressure and temperature cycles.

In fig. 12, the test pipe assembled in the facility for pressure and temperature cycles is shown.

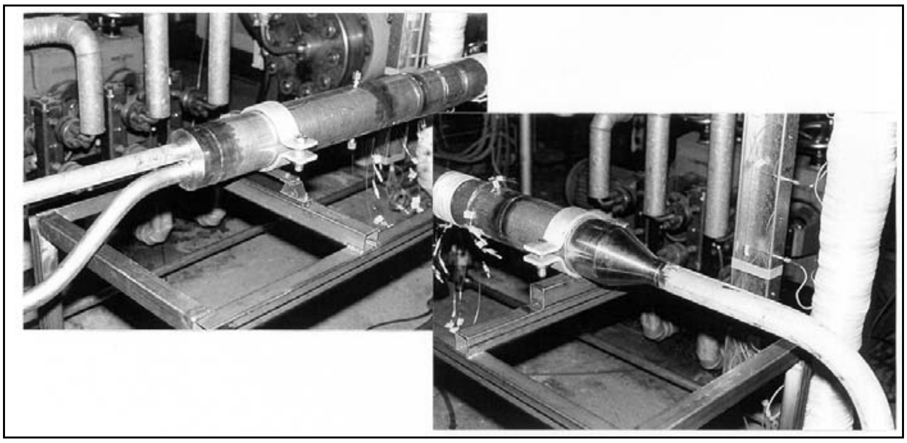


Figure 12. *Test pipe assembled for aging tests*

The according residual stresses were measured after the normal welding, the LPHSW and after operational load. The pipe with the following geometry: outer diameter: 114.3 mm, wall thickness: 6.3 mm, pipe length 700 mm, has been welded together by a 6 pass weld and an additional LPHSW in 2G - welding position (horizontal pipe axis)

In fig. 13, a cross section over the weld is given. During welding the temperatures were recorded at different positions at the inner and outer surface of the pipe. All necessary input data for the numerical investigations have also been recorded and fixed in the welding procedures (number and sequence of passes, heat input for each pass, velocity).

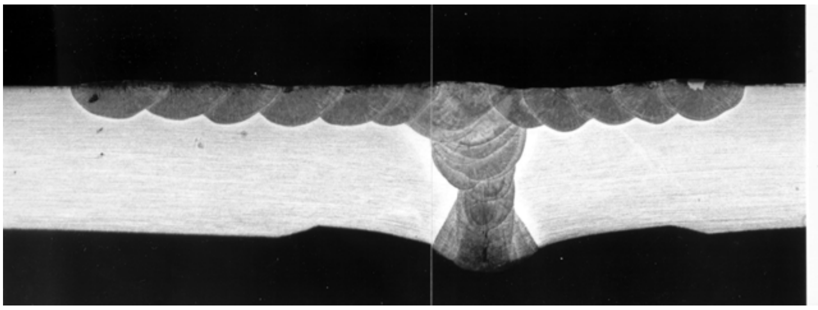


Figure 13. *Cross section of the manual TIG weld including the LPHSW*

The process of welding has been simulated under the most realistic conditions possible using the three dimensional finite element method. The mesh configuration is shown in fig. 14. For appropriate calculation with the FE-code ABAQUS, three dimensional 8 node bricks are used with reduced integration order.

The problem is treated as an uncoupled thermal and mechanical problem, first the temperature field is evaluated and from these results stresses and displacements are calculated. An elastic-plastic mixed hardening material behavior is supposed for austenitic material. All material data are introduced in the model with their temperature dependency.

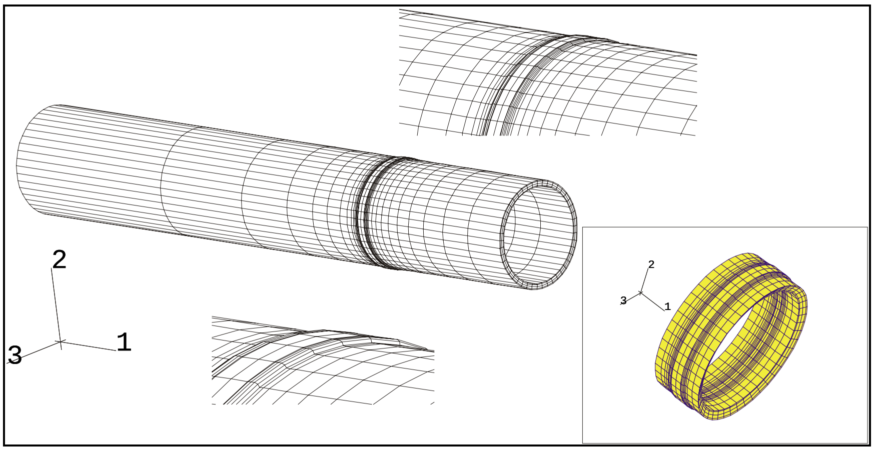


Figure 14. *Finite element mesh with details of the weld*

The welding process was simulated as a freely moving heat source controlled by corresponding time functions of the elements. Transition from liquid to solid phase was allowed for on the basis of latent heat; parameters for surface radiation and convection were also defined. The preheat and inter pass temperatures specified in the welding plans were observed for each bead. According to available information from numerous numerical parameter calculations, these parameters significantly affects the formation of the 3 D temperature and stress fields and thus, ultimately, post-weld deformation. The LPHSW was performed after the last bead of the joint weld has been welded. During welding of the LPHSW the pipe has been cooled at the inner surface with cold water.

The aging cycles after welding were performed as a restart run of the weld simulation. This means, the residual stress and deformation field after last pass heat sink welding was the basis for this analysis. The aging cycles were again performed as an uncoupled thermal and mechanical problem. After 10 cycles the analysis was interrupted, because no further effect on the stress and strain field could be observed.

The results of the simulation are mainly presented as residual stress fields during the welding process, after welding of all passes, after LPHSW and finally after the operation cycles. A comparison is made between numerical and experimental results. In fig. 15 the deformation of the pipe during welding is shown (enlarged displacement factor).

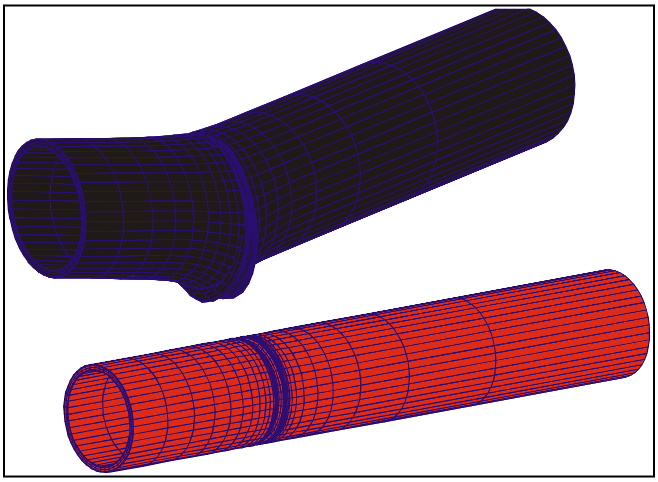


Figure 15. *Displaced structure during welding*

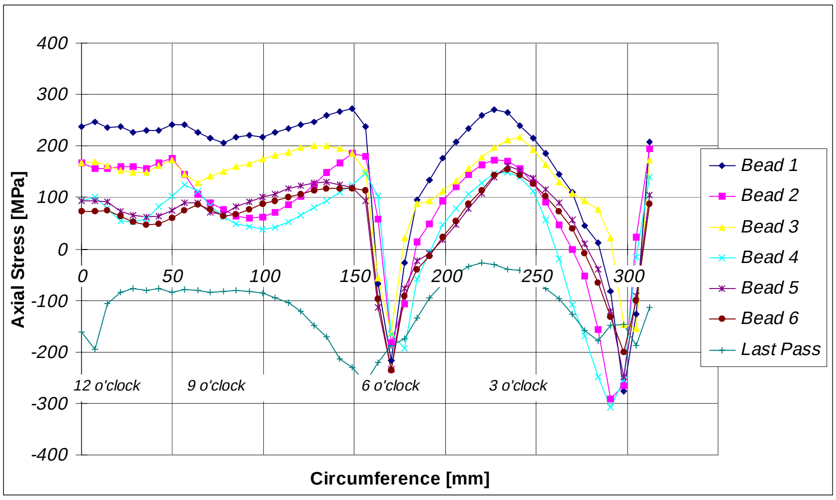


Figure 16. *Weld residual stresses in axial direction along the circumference of the weld*

The distribution of the axial stresses along the inner circumference is shown in fig. 16 for the most interesting region, the HAZ, being relevant for an IGSCC attack. As mentioned before, the distribution is quite irregular along the circumference. Because passes 1 to 6 are welded in two steps, a minimum is obtained in 6 o'clock (begin of welding) and 12 o'clock position (stop of first half of welding). After LPHSW all axial stresses at the inner surface are in compression mode not only in the position 0.2 mm from fusion line, but up to an axial distance of 5 mm from weld middle. It could be shown that:

– the residual axial stresses are not homogeneous around the circumference, this means only a 3D simulation is adequate for an according stress simulation;

– the LPHSW alters the stresses in the HAZ from tensile to compression;

– the residual stresses will be influenced by the operational load, but the compression stresses in the HAZ still remain; this means the protection against any corrosion attack is maintained.

Prediction of distortions of the ITER torus

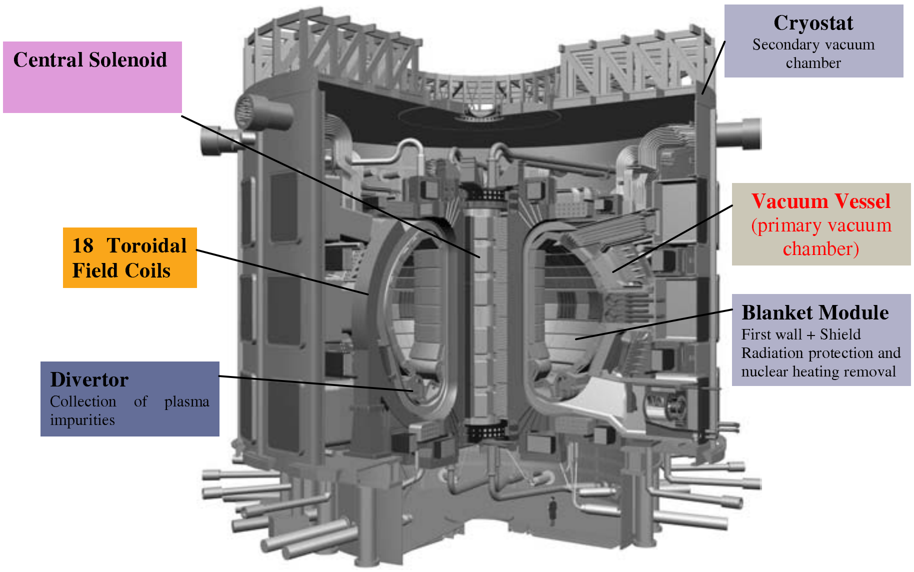


Figure 17. *Exploded view of the ITER torus*

The International Thermonuclear Experimental Reactor (ITER) Vacuum Vessel (VV) is a double wall D shaped and over 10 m high cross section torus (fig. 17). It is made of nine VV sectors manufactured in factory, transported to and assembled on site to form the complete torus. The fabrication tolerances for the whole vessel including In-pit field assembly are less than 20mm for the height and the width and even more stringent for the location of the In-vessel components supports. The selection of an optimized manufacturing scheme and the prediction of the distortions created during VV welding and in particular during field joint welding are of prime importance to judge the acceptability of the tolerance requirements and the overall feasibility of the VV manufacture.

This can be achieved through a manufacturing R&D programme involving the manufacture of partial models accompanied by numerical simulation of the welding distortions in order to validate the predictive models and then extrapolate to the complete VV structure. As a part of this program, a first study related to the prediction of field joint between two adjacent VV sectors distortions has been launched. The field joint involves the connection by 60mm thick multi-pass narrow gap TIG welds of both inner and outer shell of the VV.

It is today unrealistic to simulate in 3D the material deposition of each of the passes for 25 meter length welds. Thus, the so-called “local/global” approach (Souloumiac *et al.*, 2002) was adopted:

– Determine locally in the weld and near this one, the state of residual stress and deformation by means of thermal and thermo-mechanical calculations.

– Then transfer plastic strains on the considered complete structure. This one is discretized by means of 3D elements locally at the level of the weld and of shell elements in the other zones.

This work being in progress (with SYSWELD®), we give, as illustration, the models used for this study in fig. 18-20.

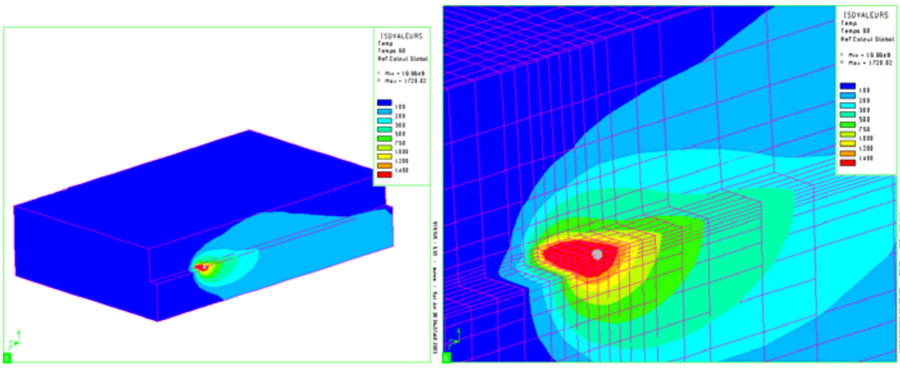


Figure 18. *Local models for thermal calculation*

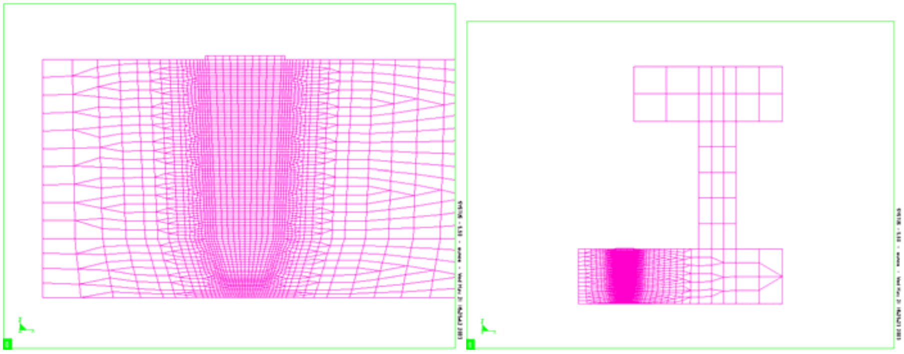


Figure 19. *Local models for thermal and thermo-mechanical calculations (inner shell)*

5. Residual stress in dissimilar metal welds

In PWR plants, most of the large components such as vessel, steam generator or pressurizer are made of ferritic steel. For preventing corrosion, these equipments are cladded with austenitic steel and, in French reactors, are connected to austenitic pipes. Thus bi-metallic welds are numerous.

5.1. *Modelling the pressure vessel cladding*

In PWR plants, pressure vessel are made of 16MND5 (A508 following ASTM standards) steel. When cladding the vessel with two layers of austenitic stainless steel strip electrode (fig. 21), intergranular defects may appear in the base metal. Therefore, when analyzing the brittle fracture behaviour of sub-clad defects, residual stresses have to be considered. The vessel is stress relieved by Post Weld Heat Treatment (PWHT). However, since cladding and base metal have different thermal expansion coefficients, residual stresses cannot be completely withdrawn. Several studies have been conducted by Framatome-ANP for assessing residual stresses in the base metal.

In all these analyses, axisymmetry has been assumed and the overlapping of layers was considered without any shift between layers. The main conclusions of these studies are the following:

– The simplified approach which assumes that the stress relief is absolute after PWHT, underestimates the stress level in the base metal.

– Residual stress fields obtained after simulation of all the manufacturing process (preheating, two layer deposits: 308L and 309L, post heating, stress relief) may be tensile in Heat Affected Zone in the base metal, even after hydrostatic test.

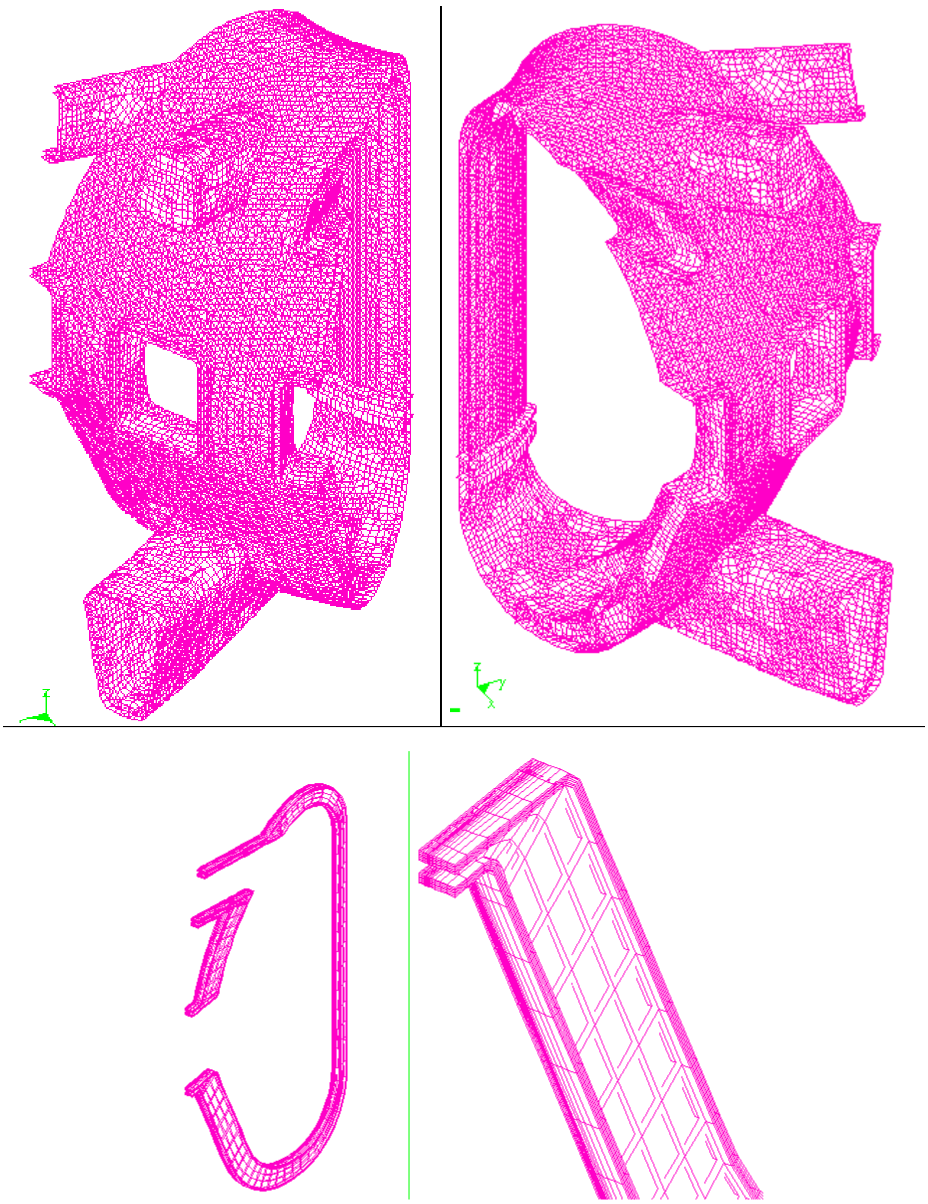


Figure 20. *Global model and 3D elements (in and near welds)*

These analyses should be worked again with more realistic hypothesis taking into account the effect of the shift between layers of cladding, the thermal fields should be computed in 3D, and viscoplasticity should be taken into account in a more refined way.

Then, the effect of the residual stresses on fatigue crack growth of underclad defects has been analyzed (Bernard *et al.*, 1989).

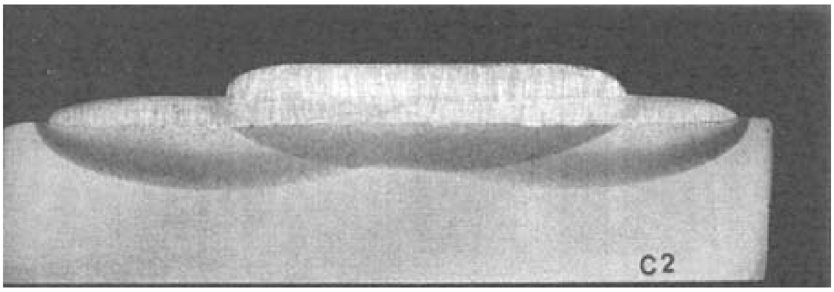


Figure 21. *Macrography of the austenitic layer deposits on a Reactor Pressure Vessel (RPV) ferritic steel*

5.2. *Modelling the dissimilar weld metal junctions*

Several studies on Dissimilar Weld Metal (DMW) have been conducted by Framatome-ANP. Recently, the company was involved in two EC projects on ductile resistance of DMW junctions in pipes: BIMET and ADIMEW. Defects are likely to appear in the brittle martensitic layer of the HAZ or between passes during buttering of welding operations. Assessment of such defects is complicated by issues that include: mis-match of yield strength of the constituent parent and weld metals, strong gradients of material properties, the presence of welding residual stresses and mixed mode loading of the defect. At present no simplified method has been validated for assessing the integrity of DMW. Residual stresses may have a strong influence on fatigue crack initiation and propagation as well as on corrosion cracking. For low toughness values, ductile crack initiation load may be lowered by residual stresses. This point is of importance since toughness values measured on bimetallic specimens decrease with the distance of the crack to the interface. Measurement of residual stress through the thickness on assembled components is unachievable. These results may be obtained using destructive techniques such as the layering removal method or in a non destructive way by neutron diffraction but in a large non-movable facility. Therefore predictive Finite Element calculations of residual stress fields are of great interest.

The simulation conducted on the 6" DMW junction BIMET is not representative, since no stress relief Post Weld Heat Treatment has been applied on this pipe, unlike it was described in the project. Thus comparison to stress measurements is of poor value. However, the study (Youtsos *et al.*, 2000) has shown the importance of modelling the entire welding process instead of assuming that residual stress in DMW are mainly induced by simple cooling down after PWHT.

In the ADIMEW (Assessment of aged piping DIssimilar MEtal Weld integrity) project (Faidy *et al.*, 2001), detailed information was available on all steps of the manufacturing process. The objective of ADIMEW project was to analyze the behaviour of defects in Dissimilar Metal Welds between pipes representative of those found in a Pressurized Water Reactor plan (surge line DMW of the French N4 reactor). The study included measurement of material properties and residual stresses, predictive engineering analysis and validation by means of a large scale test performed at 300°C.

Two 16” (450 mm diameter) DMW mock-ups were manufactured by Framatome-ANP within the programme. The first, AD01 (fig. 22), was cut-up to measure welding residual stresses and provide small-scale specimens for measurement of tensile and fracture toughness properties of the constituent parent steels, weld metals and associated heat affected zones. The second mock-up, AD02, was used for the pipe fracture test conducted in July 2003. Theses mock-ups were pipe made of a section of type A508 Class 3 ferritic pipe joining a 316 L section of type 316L austenitic pipe by means of a type 308 austenitic weld with type 308/309L buttering laid on the ferritic pipe.

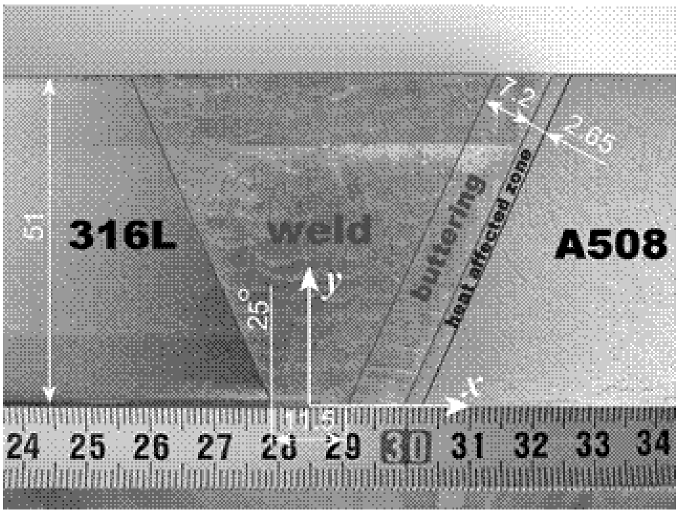


Figure 22. *Cross-section of the bi-metallic weld of AD01 mock-up*

The residual stress fields were to be determined experimentally using the Neutron Diffraction (ND) technique developed by JRC, the Hole Drilling (HD) technique developed by TWI, Cut-Compliance method (CC-method), developed by

Mat-Tec and numerically using the Finite Element Method (FEM). Framatome-ANP has performed the two following calculations:

– a simplified analysis, which consists of a cooling calculation from an assumed stress-free state after the stress-relief heat treatment;

– a detailed analysis, which simulates each elementary step of the mock-up manufacturing procedure. The simulation does not reproduce the deposit of all the beads, but models the welding by deposition of layers grouping all the beads lying in a same plane. This macrobead technique has been validated on detailed welding simulations of a thirteen pass welding of two austenitic pipes.

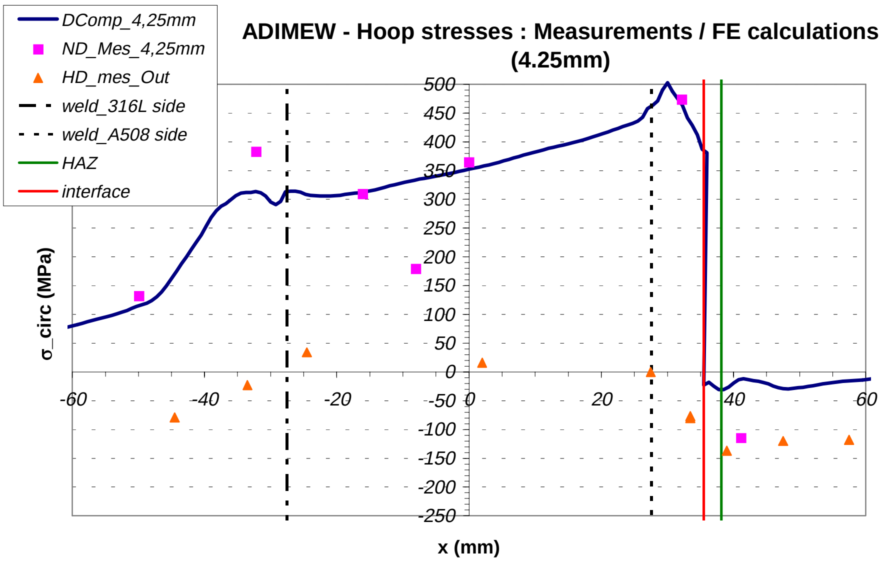


Figure 23. *Hoop residual stresses at 4,25 mm under the outer wall*

These computations are 2D axisymmetric, the self restraint is accounted for by fixing appropriate boundary conditions. An internal report describes these calculations and compares numerical results to residual stress measurements. The results will be made public soon in the final report of the project. The main conclusions of this study are:

– Large differences are observed on simplified and detailed computations.

– An excellent agreement is observed between the most reliable ND stress measurements and detailed computations (fig. 23) except in the vicinity of the root pass. These differences are probably due to a weakness of the macrobead technique when applied to the buttering.

– We attribute the differences between HD measurements and extrapolation of ND measurements on the walls to machining. The heating due to machining may induce considerable compressive stress on a thin layer under the surface. This effect has not been modelled in the residual stress simulations.

– Tensile axial residual stresses are predicted along the crack location, therefore producing an increase of the crack driving force J. However, the residual stress fields are not likely to influence the crack initiation since the crack initiates when the ligament is fully yielded. A similar observation has been made on the smaller BIMET component.

6. Conclusion. Framatome-ANP knowledge in welding simulation and future prospects

Residual stresses, distortions, structural material changes due to welding may reduce significantly the strength, the resistance to damage and the function of welded structures. Welding Numerical Simulation (WNS) is liable to give detailed information on all these parameters as well on the efficiency of the mitigation actions. However the reliability of WNS requires experience, tools and data for the numerical computation of temperature fields, possible phase transformations, strains and stresses induced by welding.

The studies presented in the paper have revealed and partially solved the following problems of WNS:

– Development of physical models representing heat input and welding phenomena,

– Validation of these models, which includes the problem of the measurement accuracy,

– Acquisition of required material properties,

– Development of tools or/and simplified approaches for 3D analyses.

Framatome-ANP develops its ability to solve these problems through a three folded approach:

– Consolidation of our knowledge in welding simulation,

– Developments of partnerships concentrated on model validation, data bases,

– New insights on welding process modelling by developing a network of competences with other industries.

On a basis of a large number of development and validation studies, creation of dedicated tools and methods, Framatome-ANP has acquired a strong capability to use TIG welding simulation on an industrial scale. Our participation to ADIMEW leaded to quite acceptable predictions of residual stress fields in DMW joints. We intend to improve our knowledge in that field. Our German technical centre has performed several studies on industrial stainless steel components.

Partnerships with INSA-Lyon and ESI-group have produced a complete validation file of thermo-mechanical models accounting for structural changes for 16MND5 and 316L welding. This fruitful cooperation continues on two themes: robustness of welding simulation and defect initiation during welding. A partnership with Troyes Technical University (UTT) and two Chinese Universities (Tshingua, Xian-Jiaotong) on residual stress measurements leaded namely to the set up of an inverse method for residual stress measurements (Cao *et al.*, 2002).

One single company cannot transform R&D results in a new industrial practice: confidence in technical results comes usually from shared experience (benchmarks, references) and creation of a scientific community in the field favours the acceptation by Safety Authorities of industrial applications of a numerical simulation technique. Therefore, Framatome-ANP decided in 2002 to create inside the French "Association Française de Mécanique", a technical committee on Welding Numerical Simulation. The aim of this committee is to develop a large network between industrial companies, scientific institutes and universities for improving our understanding of all physical phenomena connected to welding and developing their numerical simulation. The WNS committee transfers information, organizes seminars, defines test cases for validation, contributes to the creation of new partnerships or actions between industrials and academics.

To the memory of André Pellissier-Tanon, who promoted since the beginning all Framatome-ANP R&D efforts in welding simulation, and helped the engineers to obtain practical solutions while always keeping a critical mind on their quality.

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