PIPEWELD, A SOFTWARE SUITE FOR COMPUTATIONAL WELDING MECHANICS FOR NUCLEAR APPLICATIONS

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ABSTRACT

In the nuclear industry, numerical modelling of welding processes has become a key tool for understanding and decision-making. It is used to evaluate the impact of welding on degradation mechanisms and to accelerate the development and qualification of welding and repair techniques. Computational welding mechanics, which involves modelling the solid-state effects of welding on the base material and weld metal, such as temperature fields, microstructural evolution, and stress-strain distributions, serves this purpose.

Since 2021, EDF has observed stress corrosion cracking (SCC) in certain austenitic stainless-steel pipe-to-elbow welds within safety injection systems. Accurate prediction of welding residual stresses (WRS) is essential for assessing the structural integrity of components exposed to SCC and similar degradation mechanisms. During welding, coupled thermo-mechanical and metallurgical phenomena occur, including microstructural transformations such as dynamic recovery and recrystallization. These transformations influence the material's hardening behaviour and must be accounted for in residual stress simulations.

In the as-welded condition, multi-pass circumferential butt welds in austenitic stainless steel typically exhibit a residual stress profile characterized by a shell bending effect. This results in compressive axial stresses in the inner half of the weld wall, although tensile zones may still develop near the weld axis on the inner surface. This behaviour is well-documented in the literature and has been validated through simulations using code-aster (a general-purpose finite element software for solid mechanics) and confirmed by experimental measurements on mock-ups.

In this context, the Pipeweld software suite has consolidated over two decades of research on welding and its numerical modelling. Built on code-aster and Salome_Meca, numerical software developed by Electricité de France, Pipeweld enables the prediction of residual stress states for component lifetime assessment and process qualification optimisation.

Keywords: welding residual stress assessment, multipass welding, computational weld mechanics, open-source based software

INTRODUCTION

In the nuclear industry, numerical modelling of welding processes has become a tool for understanding and decision-making, used to assess the effect of welding on certain degradation mechanisms and to accelerate the development and qualification of welding and repair techniques. Computational welding mechanics, which involves modelling the effects of welding in the base metal and the weld in the solid state (temperature field, microstructure, stress, and strain distribution), can be implemented for this purpose.

Significant R&D efforts have contributed to the advancement of modelling approaches, particularly in determining the appropriate level of accuracy required for industrial applications. To support EDF engineers, who are conducting an increasing number of studies, the development of the Pipeweld tool was initiated. This tool aims to standardize the methodology for numerical welding simulations by capitalising over 20 years of R&D, thereby enhancing the consistency and quality of engineering assessments.

COMPUTATIONAL WELDING MECHANIC MODELLING FOR THE PREDICTION OF THE RESIDUAL STATE

PRINCIPLES

From the perspective of continuum mechanics, computational welding simulation enables the prediction of the residual mechanical state of a welded assembly by evaluating the distribution of residual stresses, distortions, and strain hardening. This residual state is intrinsically linked to the entire thermal and mechanical history of the welding process. Consequently, its assessment requires the computation of the thermo-mechanical equilibrium of the welded structure throughout the welding operation.

The energy input from welding propagates through the structure primarily via heat conduction. Numerical simulation enables the prediction of temperature evolution at any point within the structure, resulting from this heat diffusion. At the structural scale, the thermal behaviour during each stage of the welding sequence is characterized by spatial temperature gradients, which are the main drivers of the component’s mechanical response.

These thermal gradients induce thermal strain gradients, leading to strain incompatibilities that generate internal stresses, particularly in regions close to the weld, as illustrated thanks to numerical modelling [1]. These internal stresses cause plastic deformation of the material, which accumulates as strain hardening throughout the welding process. The coupling and interaction of physical phenomena described above are illustrated on Figure 1.

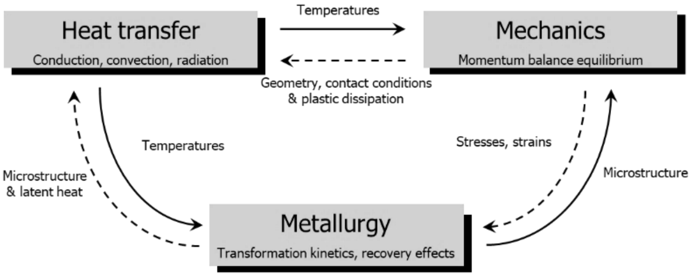


Fig. 1 Coupling and interaction for WRS assessment: heat transfers, metallurgical phenomena and mechanical consequences

In the specific case of butt welding between two pipes, groove deformation also plays a significant role in the development of strain hardening near the weld. Additionally, structural effects, commonly referred to as the "diabolo" effect, must be considered when analysing the distribution of certain components of the stress tensor. For example, shell bending induced by radial and axial shrinkage in butt-welded pipe joints affects the axial stress, which typically exhibits an S-shaped profile across the thickness at the weld centreline [2]. This is illustrated in Figure 2, where tensile stress peaks on the outer surface (first loop of the "S") and compressive stress peaks on the inner surface (second loop).

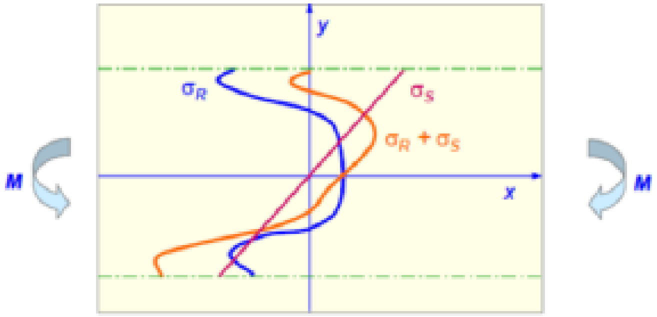


Fig. 2 Superposition principle of bending stresses (σ_s) across the wall thickness with residual stresses (σ_r) not associated with bending effects

The numerical evaluation of the residual state in welds requires accounting for the physical phenomena described previously. These phenomena are governed by a set of equations that are numerically solved using the finite element method (FEM). The parameters that feed into these equations and define each specific welding configuration are identified through the analysis of Welding Procedure Specifications (WPS).

GEOMETRIC MODEL AND MESH

As with any numerical method, it is necessary to discretize both physical time and physical space. These temporal and spatial discretization must be refined to accurately capture the thermal gradients that drive the physical quantities of interest.

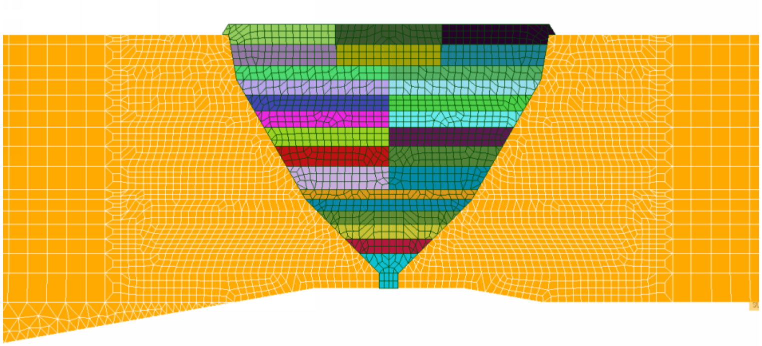


Fig. 3 Example of 2D mesh of a butt weld with each bead in different colour

The assembly of the components of interest, such as thick-walled piping systems (thickness > 10 mm), is typically performed using multi-pass welding. Simulating such operations requires accounting for a dynamically evolving geometry, which changes according to the weld groove filling sequence. The initial geometry consists of two chamfered components aligned end-to-end. This geometry evolves with each welding sequence as weld beads are progressively added to fill the groove (illustrated on Figure 3). The position and dimensions of each weld bead are determined based on the operating parameters of the specific welding sequence and the diameter of the filler metal used.

THERMAL MODELLING

The thermal model is employed to simulate the heat input during welding by representing it as an equivalent heat source. It enables the analysis of heat transfer within the structure through conduction. The thermal field evolution predicted by the numerical simulation is governed by the thermo-physical properties assigned to the constituent materials of the assembly, as well as by the boundary conditions accounting for convective and radiative heat exchange with the surrounding environment. The implementation of the thermal model yields a spatio-temporal temperature distribution, providing detailed insight into the thermal history of the welded structure.

The heat input is modeled:

- in 2D modelling, as a surface heat flux applied to the 2D cross-section under analysis
- in 3D modelling, as a volumetric heat flux applied to the 3D bead or bead section.

Its spatial distribution around the deposited weld bead is defined by geometric parameters (triangular distribution or double-ellipsoid [3-4-5]) and from welding engineering heuristics, considering:

- a dilution rate of approximately 50% for the initial pass (root pass),
- a dilution rate of approximately 30% for all subsequent passes.

The spatial profile of the heat flux is thus governed by these parameters to reflect realistic energy deposition. For each welding sequence, the consistency between the actual input power, calculated as the product of current, voltage, and process efficiency, and the power implemented in the numerical model is systematically verified to ensure physical accuracy.

Heat conduction within the assembly is governed by two material-dependent parameters: thermal conductivity and volumetric heat capacity (the product of specific heat capacity, cp, and density, ρ). Both parameters are temperature-dependent, and accounting for their variation is essential in fully coupled thermo-metallurgical simulations, introducing nonlinearity into the thermal model's solution.

MECHANICAL MODELLING

In the absence of external stress, the mechanical consequences of the welding operation are related to the presence of thermal gradients in the thermo-mechanically affected zone during welding. The definition of the thermal loading is therefore essential to establish the stress at the origin of the WRS. These thermal deformations are accommodated by the structure in the form of local elastic and inelastic deformations on which are superimposed global internal forces induced by the self-bridging effects caused by the massive parts that remain cold at the scale of the structure (tourniquet effect for example). In multi-pass welding, the WRS thus originate from the succession of shrinkage and expansion that are counteracted or even blocked by the colder and therefore stiffer parts of the assembly.

The evolution of residual welding stresses is thus dependent on the choice of laws linking stresses and strains, which can be broken down into an elastic part, thermal and inelastic $\dot{\varepsilon} = \dot{\varepsilon}^{e} + \dot{\varepsilon}^{th} + \dot{\varepsilon}^{in}$ and the way of describing plasticity (permanent inelastic deformation at the origin of the WRS and governing the variables modifying the elasticity domain by strain hardening). In this respect, the behavior law used to translate plasticity integrates phenomena of work hardening recovery characterized specifically to describe the behavior of alloys that do not present a phase transformation in the solid-state during welding (FCC alloys at any temperature such as Ni base alloys or austenitic stainless steels) [6]. Note that a weak coupling (sequential chaining of thermal, metallurgical and mechanical analyses at each welding pass) is sufficient for the determination of the WRS for the concerned assemblies as shown in the diagram of Figure 1.

The Von Mises threshold function σ_{eq} or equivalent stress in the sense of Von Mises which corresponds to the second invariant of the stress tensor σ_{ij} whose $\underline{s}$ is the deviatoric part, is generally used to characterize the stress state in metallic materials:

$$f(\sigma_{ij}) = \sigma_{eq} = J_2(s_{ij}). \tag{3}$$

An isotropic work hardening of the material is considered. σ_0 is the initial yield strength of the unhardened material (initial yield strength); it is a function of the temperature θ. Let R be the increase of the yield strength by work hardening of the material, which is dependent on the temperature and the irreversible deformation p (cumulated plastic or viscoplastic deformation which represents the work hardening parameter). The yield strength of the strain-hardened material is written:

$$\sigma_y(p,\theta) = \sigma_0(\theta) + R(p,\theta), \tag{4}$$

$$\text{where } p = \int_0^t \dot{\varepsilon}_{eq}{}^{p}.dt \quad \text{and} \quad \dot{\varepsilon}_{eq}{}^{p} = \dot{p} = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}^{p}.\dot{\varepsilon}_{ij}^{p}}$$

The physical strain hardening model is supplemented by a recovery term. Thus, the creation of plastic deformation without strain hardening recovery is affected by a recovery term which depends on the temperature, knowing that this effect is thermally activated above 600°C and that its evolution rate increases with the temperature. The recovery of work hardening is modeled by the following equation:

$$\dot{r}(t) = \dot{p}(t) - k(\theta(t))\langle r(t) - r_\infty(\theta(t))\rangle \tag{5}$$

With:

r: cumulated plastic strain with consideration of the strain hardening recovery,

k: coefficient which characterizes the dynamics of recovery according to the temperature and which depends on the considered material,

r_∞: coefficient which characterizes the threshold quantity of plastic deformation which cannot be recovered, and which depends on the temperature and the considered material,

$\langle x\rangle$ denotes the positive part of x.

The two coefficients k and r_∞, which are defined above, are material parameters characterized from specific tests (see [6]).

QUANTITIES OF INTEREST AND POST-PROCESSING

Post-processing of the thermo-mechanical simulations results enables a comprehensive assessment of the welded assembly, including both geometric and mechanical characteristics:

- Characterization of metallurgical zones:
  - Fusion Zone (FZ): region where the material has melted and resolidified,
  - Heat-Affected Zone (HAZ): region subjected to thermal cycles without melting,
  - Thermo-Mechanically Affected Zone (TMAZ): region influenced by both thermal and mechanical effects.
- Evaluation of the residual state of the assembly:
  - Groove shrinkage due to thermal contraction,

  - Root penetration anomalies (e.g., excess or lack of material, root bead formation),
  - Global structural distortion, including bending or warping,
  - Residual stress distribution throughout the joint and surrounding material,
  - Mapping of accumulated plastic strain, providing insight into localized permanent deformation.

For SCC issues, residual stresses are not the only mechanical quantity to evaluate, strain hardening is also important as initiation and propagation laws used for SCC modelling (initiation, orientation and kinetic) depends on both stress and strain hardening [7]. Strain hardening or equivalent plastic strain that drives the material sensitivity to SCC are implicitly computed during computational welding simulation [8] and directly correlated with hardness measurements as those presented in Figure 4. Correlation rules based on the same relationship that the one established in [9] between strain hardening and hardness are illustrated in Figure 4.

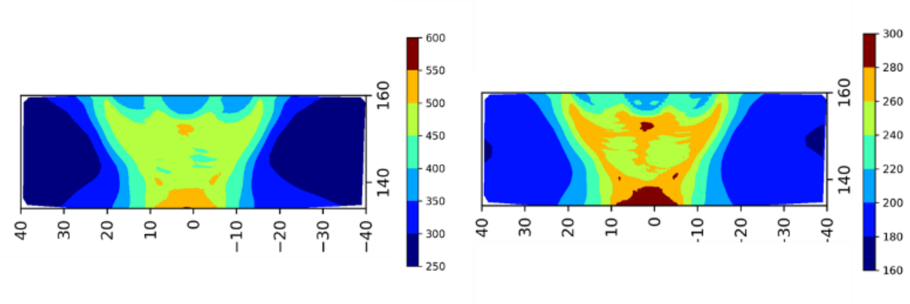


Fig. 4 Updated yield strengh in the simulated weld region and TMAZ (left) and conversion into a hardness map (right)

VALIDATION PROCESS

Model validation relies on the comparison between simulation results and experimental measurements conducted on two types of mock-ups. Semi-industrial mock-ups are designed to replicate the complexity of welding operations without being specific to any assembly. For this type of model, it is very useful to have a large number of measurements taken using different methods, as well as different models created by different teams. This is why it is very useful to rely on the The European Network on Neutron Techniques Standardization for Structural Integrity (NeT) [10] to create these models. In contrast, industrial mock-ups are developed to closely resemble actual components, considering factors such as scale, number of weld passes, and geometric configuration.

SEMI-INDUSTRIAL MOCK-UPS: NET NETWORK CONTRIBUTION

The European Network on Neutron Techniques Standardization for Structural Integrity aims to advance both experimental and computational methods, as well as standards, for the accurate characterization of WRS. Established in 2002, NeT operates through in-kind contributions from a wide range of partners in industry, academia, and research institutions.

Each configuration studied within the network is managed by a dedicated Task Group (TG), responsible for producing mock-ups, conducting measurements and simulations, and interpreting the results. NeT's work has led to approximately 85 academic publications and has supported over 10 PhD theses in related scientific fields. Notably, two special issues of the International Journal of Pressure Vessels and Piping - published in January 2009 and July 2018 - highlighted the findings of Task Groups TG1 and TG4, respectively.

One of NeT's most significant achievements is fostering international industrial consensus on the development of predictive and robust numerical models for residual stress, supported by access to high-quality experimental data from well-controlled mock-ups, primarily measured non-destructively using neutron diffraction. Research from NeT played a key role in the development of the draft international standard ISO 21432:2018 on residual stress determination via neutron diffraction and contributed to ISO/TS 18166:2015 on numerical welding simulation, particularly for nuclear applications.

NeT's studies are driven by the imperative to ensure the safety and reliability of critical welded components in the nuclear sector. The results are highly relevant to industry. EDF has highlighted how NeT has enabled them to validate numerical stress predictions in the context of nuclear plant lifetime management and safety. Of particular interest to EDF are Task Groups TG4, TG6, and TG8, which focus on nuclear-related applications.

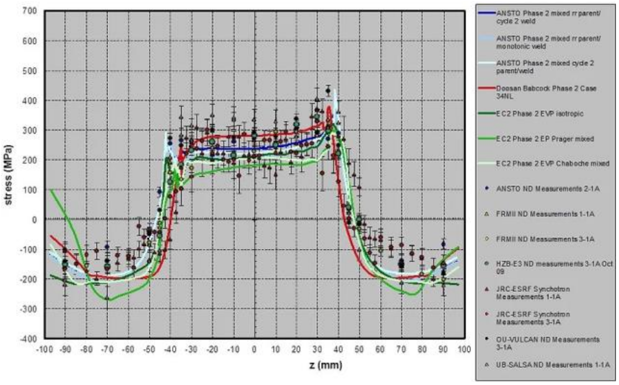


Fig. 5 TG4 – Transverse residual stresses along a line 5 mm below the surface of the welded plate in the welding direction, measurements (points) and simulations (lines) [11]

TG4: 3-Pass Slot Weld (Stainless Steel)

Task Group 4 (TG4) [11] was launched in 2007 to build upon the advancements achieved in TG1 by addressing a more complex scenario. This group focused on investigating residual stresses in a specimen made from an AISI 316L(N) austenitic stainless-steel plate, which featured a central groove. The groove was filled using three overlapping TIG weld passes of AISI 316L stainless steel, applied through a mechanized TIG welding process. This mock-up configuration is representative of a short and shallow weld repair geometry, notably one that does not include the original weld.

TG6: 3-Pass Slot Weld (Ni alloy)

Task Group 6 (TG6) [12-13] is closely based on the TG4 design, with the only distinction being the choice of materials: the specimen consists of an Alloy 600 plate welded using Alloy 82 filler metal. As such, it shares all the advantages and challenges of the TG4 configuration, including the development of a complex three-dimensional residual stress field within a compact and portable specimen. This makes it well-suited for rapid residual stress measurements using a variety of techniques. The specimen contains a substantial volume of weld metal that has undergone multiple high-temperature thermo-mechanical cycles, contributing to the complexity of the residual stress distribution. The fabrication, measurement, and simulation protocols are defined by EDF in collaboration with domain experts, and the mock-ups are manufactured by EDF R&D.

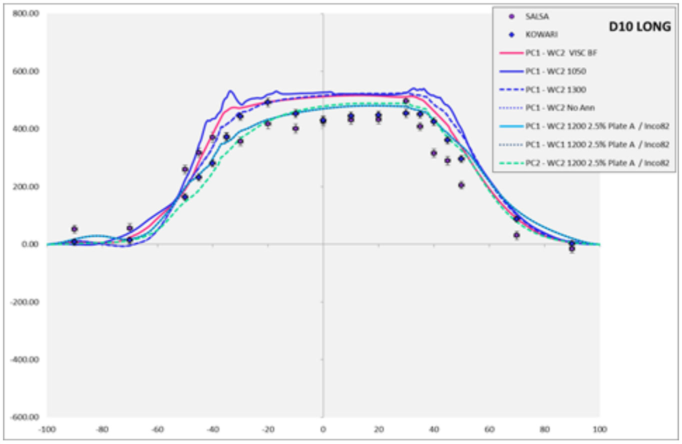


Fig. 6 TG6 – Longitudinal residual stresses along a line 10 mm below the surface of the welded plate in the welding direction, measurements (points) and simulations (lines) [ref]

TG8: 5-Pass Slot Dissimilar Weld (Ni alloy) on Ferritic Steel

Task Group 8 (TG8) [14] focuses on a steel plate made of French grade 18MND5, featuring a five-pass slot weld performed using nickel-based Alloy 52 consumables. This group was formed to address challenges related to weld repair procedures. The TG8 round robin specimen is closely modelled on the TG4 design, with the key difference being an increased plate thickness of 30 mm. This enhancement provides improved self-clamping conditions and helps minimize distortion. As with TG4, the TG8 specimen generates a complex three-dimensional residual stress field within a compact and portable geometry, making it well-suited for rapid residual stress measurements using various techniques. The specimen includes a significant volume of weld metal subjected to multiple high-temperature thermo-mechanical cycles. The use of a nickel-based filler metal introduces additional complexity in residual stress characterization. Moreover, the configuration exhibits a complex mismatch behaviour between the weld and base metal, involving phase transformations and tempering effects in the Heat Affected Zone (HAZ). The fabrication, measurement, and simulation protocols are defined by EDF in collaboration with domain experts, and the mock-ups are manufactured by EDF R&D.

INDUSTRIAL MOCK-UPS

It is often necessary to have a model that is even more representative of the type of assembly to be studied, considering the complexity of the geometry and the welding process used (and therefore the greater number of welds). For this purpose, industrial models can be produced, which will be more complex and more expensive to manufacture [15].

For austenitic steel pipe assemblies, we present an example of a model that was instrumented with thermocouples to evaluate the thermal conditions experienced by the assembly. In addition, stereo correlation measurements were performed to evaluate the deformations of the assembly.

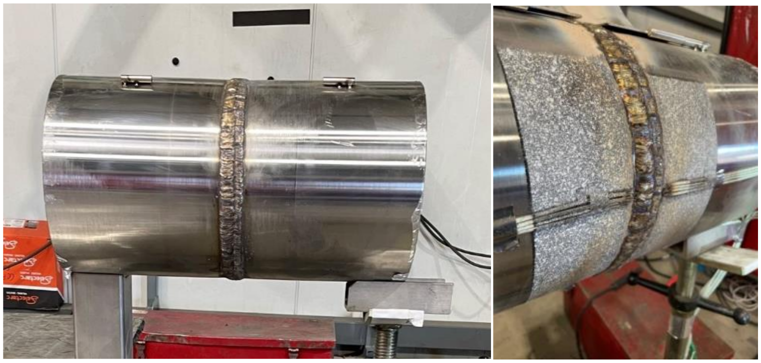


Fig. 7 Austenitic steel pipe mock-up with thermocouples instrumentation and speckles for stereo correlation analysis

Finally, residual stress measurements are performed in the thickness (X-ray diffraction [16] and deep hole drilling method [17]) to characterise the residual state. Comparison with simulations allows the numerical approach to be validated.

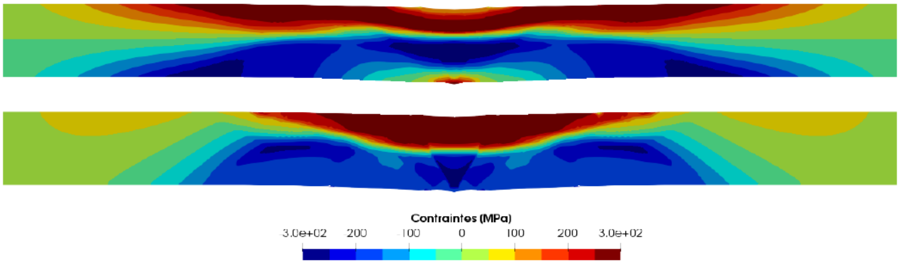


Fig. 8 Example of residual stress in a mock-up pipe predicted with simulation: (top) axial stress, (bottom) circumferential stress

PIPEWELD: FROM A RESEARCH KNOWLEDGE CAPITALIZATION TOOL TO AN OPERATIONAL INDUSTRIAL SOLUTION

In the context of welding and repair processes for PWR primary circuit components, the Pipeweld software suite has enabled the capitalisation of two decades of research on welding and its numerical modelling. Pipeweld is based on code-aster [18], an open-source generalist software of simulation in mechanics and in structural analysis developed by EDF for more than 30 years, from Salome-Meca plateform [19], an all-purpose plateform for mechanical analysis which offers the entire calculation chain from CAD, meshing to post-processing. Pipeweld can predict residual states for lifetime assessment and to optimise process qualification. Pipeweld's development was initiated to support the numerical welding simulations (NWS) which were essential for SCC estimations. The development of this tool was motivated by the following needs:

- consolidate and standardise the methodology for numerical simulation of welding (in 2D and 3D), initially limited to the assembly of butt pipes;
- facilitate the production of the necessary input data, particularly the meshes, using a parametric approach;
- facilitate multi-parametric studies;
- facilitate post-processing of results and standardise outputs for the quantities of interest;
- facilitate the transfer of welding simulation results as input data for SCC analysis (crack initiation and propagation) or brittle fracture;
- facilitate the creation and enrichment of a Verification and Validation (V&V) file;
- provide a framework for studies under quality assurance, which is mandatory for the nuclear safety authority.

The ambition of the Pipeweld tool is to be adopted by engineering teams as a qualified scientific computing tool for conducting studies aligned with established industrial practices in the field. These practices are defined in several standards, notably AWS [20] and ISO [21], as well as their adaptations for application within the French nuclear sector, such as the French Nuclear Institute guideline [22].

Pipeweld enables robust CWM studies, covering the entire workflow from the geometric design of the weld groove to the post-processing of simulation results. Each stage of the process is handled within a dedicated sub-module, as illustrated in Figure 8.

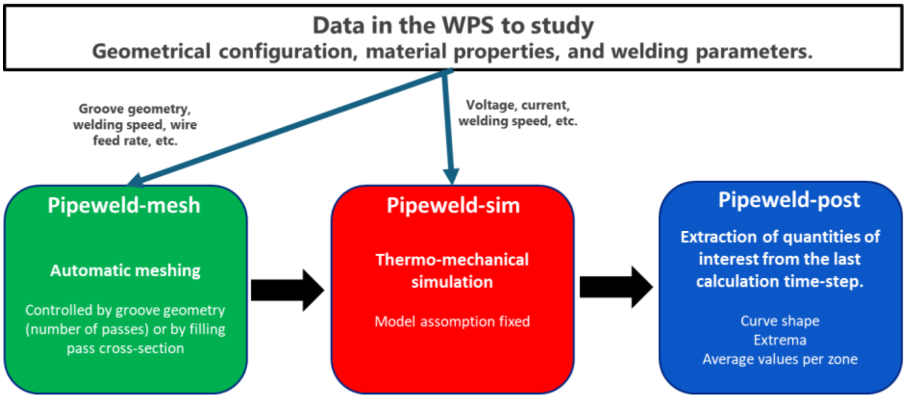


Fig. 9 Pipeweld tool workflow chart

APPLICATIONS

RESIDUAL STRESS PREDICTION IN MULTI-PASS PIPE CIRCUMFERENTIAL BUTT WELDS TO FOR SCC RISK CLASSIFICATION

Prediction of residual stresses in welds is essential to evaluate the integrity of a component subject to degradation mechanisms such as Stress Corrosion Cracking. During welding operations, complex thermo-mechanical and metallurgical processes take place and lead to microstructural changes such as dynamic recovery and dynamic recrystallization. These microstructural changes induce a modification of hardening behaviour that should be considered to accurately evaluate residual stresses through numerical simulations. In the as-welded conditions, multi-pass pipe circumferential butt welds made of austenitic stainless steel show a typical residual stress profile through the wall of the welded joint. Such a shell bending profile places the inner half of the weld joint wall and its vicinity in compression in the axial direction. However, tensile zones can appear in the inner wall near the axis of the weld.

A large simulation campaign was carried out to cover different welding configurations and confirm these trends [8]. This digital chart is built based on a design of experiments of 100 numerical simulations of welding per diameter and schedule. The parameters are:

- Diameter, thickness,
- Welding processes (GTAW, SMAW…),
- Groove shape.

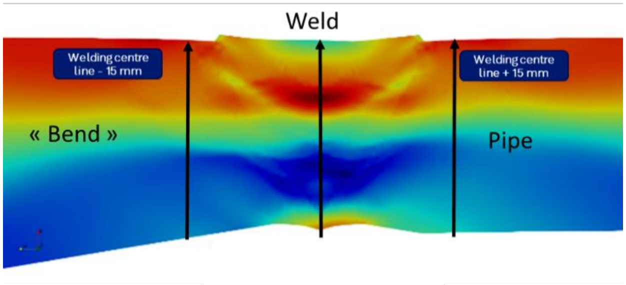


Fig. 10 Typical axial stress state from simulation [8]

This set of simulations show the systematic presence of a compression zone on the inner side, with some variability depending on the welding conditions and geometry. The classification of SCC risk is then defined by a set of two indicators that can be related to crack initiation (stress, strain hardening near the surface) and propagation (stress, strain hardening in the bulk).

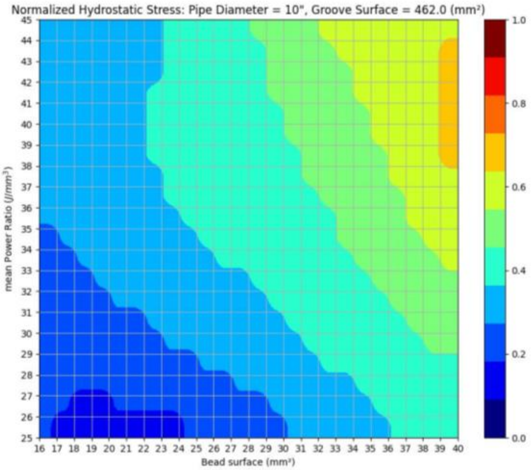
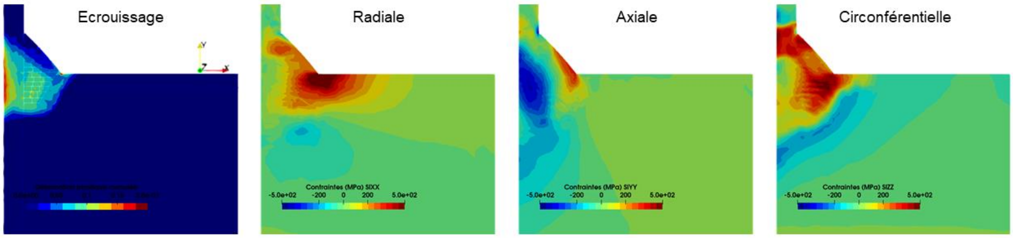


Fig. 11 Hydrostatic stress map as a function of the bead surface and the power ratio for a 10" diametre and a groove section of 462 mm^2 [8]

Bottom Mounted Nozzles (BMNs) are welded components located at the lower part of a nuclear reactor pressure vessel, designed to allow the passage of instrumentation. Typically fabricated from nickel-based alloys, these components are welded to the vessel wall, which is generally made of low-carbon steel. Due to their critical function, BMNs must comply with stringent safety standards, particularly in terms of weld integrity and sensitivity to SCC.

Pipeweld has been extended to enable 2D modeling of BMN configurations, considering the specific challenges associated with these assemblies, notably the presence of multiple materials. The tool's capability to handle a wide range of BMN configuration has been demonstrated. The validity of the simulation results has been assessed through comparison with available reference data, including previous numerical studies and experimental measurements on mock-ups. An illustrative example is presented in Figure 12. In this case, four materials were considered: Inconel 600 for the BMN tube, 16MND5 reactor vessel steel for the vessel bottom, Inconel 600 for buttering and weld beads, and 316L stainless steel for the vessel cladding. The Figure 12 compares the results of a 3D simulation of a central BMN (with a 0° inclination) with 2D results obtained using Pipeweld.

a) PFC centrale : résultats 3D



b) PFC centrale : résultats 2D

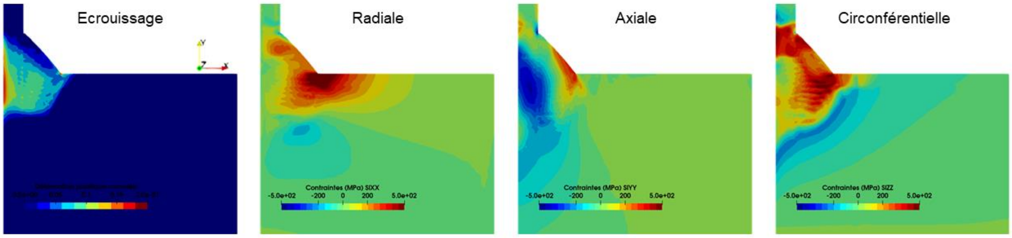


Fig. 12 Comparison of residual state obtained and strain hardening with 3D modelling (top) and 2D modelling (bottom)

A very good agreement is observed across all components, both in terms of stress distribution and strain hardening. This case study highlights the ability of Pipeweld to significantly reduce the time required for simulation input preparation and the post-processing time thanks to the parametric approach, thereby improving overall modeling efficiency, while maintaining methodological consistency across different simulation approaches.

CONCLUSIONS AND FUTUR DEVELOPPMENTS

The Pipeweld software suite represents a significant advance in the field of computational welding mechanics (CWM) for nuclear applications. Consolidating more than two decades of research and development within EDF, Pipeweld offers a robust, standardised and validated framework for simulating welding processes and predicting residual stress states. Its integration with open-source platforms such as code-aster and Salome_Meca ensures methodological transparency and adaptability to a wide range of industrial configurations.

Thanks to rigorous validation against semi-industrial and industrial models, including contributions from the NeT network, Pipeweld has demonstrated high fidelity in reproducing complex thermomechanical phenomena. Its predictive capabilities are essential for assessing the structural integrity of components exposed to degradation mechanisms such as stress corrosion cracking (SCC) and for supporting life management strategies in nuclear power plants.

Future developments will focus on extending Pipeweld's applicability to more complex geometries (as illustrated in [23] on a repaired weld), multi-material assemblies (in particular, materials with metallurgical solid state transformation), improving the automation of model configuration and post-processing, and integrating with broader safety assessment workflows. In addition, a verification and validation file will be compiled based on cases of interest for which measurements (particularly deformations and residual stresses) are available or, failing that, simulation results obtained in round-robin tests. These improvements aim to make Pipeweld a qualified engineering tool, compliant with international standards and suitable for deployment in safety-critical environments.

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