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The Numerical Simulation of Welding in Europe : Present Capabilities and Future Trends †

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Abstract

The numerical simulation of welding processes has entered a new age. The physical background and its numerical counterpart have been investigated for more than 20 years. The expected benefits of such simulation are not only the process calibration in term of feasibility (distortions occurring during welding for example) but also the final distortion and the influence of welds on the in-service behavior of components. This article focuses on the metallurgical and thermo-mechanical aspects. Industrial applications are presented to illustrate the present capabilities.

KEY WORDS: (Welding Simulation) (Welding Distortion) (Residual Stress) (Metallurgical Transformation) (Local/Global Approach) (SYSWELD)

1. Introduction

The objective of this article is to describe the state-of-the-art and the trends in the numerical simulation of welding processes. We will mainly focus on the European efforts in this domain.

First of all, a quick historical vision of the development of the welding simulation in Europe is conducted. Then, the expected benefits of the simulation of welding are detailed to introduce the physical phenomena involved and their modeling. Metallurgical models, which are a key point of such simulations, are detailed as well as the ways used to model the different couplings. Then, the finite element implementation of those models is explained. At last, industrial applications are presented. As a conclusion, the recent developments of models and technologies are discussed.

2. Welding Simulation from an Historical Point of View

First, as history is definitively not an exact science, the authors apologize for any mistake or lack. We have limited this chapter to the very beginning of welding simulation.

The very first request of simulation of residual stresses in welded component has been initiated at the end of the 70th by the nuclear regulation authorities. The European countries involved in the development of nuclear power plants : Great Britain and France and with less conviction Germany had realized that the potential danger of such plants requires an accurate analysis of the defects and of their consequences. The codification has been written using simple mathematical laws. Unfortunately, the manufacturing operations can induce high stress gradients making those laws inapplicable. It was clear that numerical investigations were needed as well as standardized experiments.

A new method, the finite element method, developed in the 70th and already used for the nuclear components has appeared to be the best solution.

In France, the very first developments for the numerical simulation of welding have been initiated by Framatome. In 1982, it was possible to simulate the full welding operation of low-alloy steels from the thermal, metallurgical and mechanical point of view. Many details can be found in the next sections.

As concerns UK, the development of new techniques for the finite element calculation of residual stress and microstructure by simulation of the welding process itself did not really begin in the electricity generation industry until the early 1990s. Prior to this, only a limited amount of work had been done using existing plasticity models in commercially available codes such as ABAQUS and SYSTUS. The major

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emphasis of technical support computation, particularly in the nuclear side of the industry, was focused on service life prediction in the as-fabricated condition given particular initial defects - in other words, fatigue, fracture and, where appropriate, creep.

A great deal of work, however, was carried out during the 1980s in specialist areas that contribute to the whole process of welding simulation. This was particularly the case in the field of metallurgy, although the activity was not, in general, directed towards computation. A classic exception to this rule was a computer model for the prediction of heat affected zone microstructures[1)] from the Central Electricity Generating Board's Marchwood Engineering Laboratories. This group produced a number of papers in the general area of weld assessment and procedures, for example[2)], in addition to further numerical approaches[3-5)].

The concentration on physical metallurgy within the CEGB at the time mirrors similar work pursued at the University of Cambridge. Indeed, no account of the history of weld modeling would be complete without mentioning the work of Ashby and Easterling, both authors of landmark texts on metallurgy[6,7)], and later, Bhadeshia. Some of this research was conducted in close collaboration with the aforementioned authors from the CEGB. A much-cited paper on grain growth from the beginning of the decade is Ref.8). As may be expected, much of the research at Cambridge was fundamental, with the objective of predicting physical properties from first principles, i.e. from chemical composition and thermodynamics[9,10)].

Within the CEGB, attempts to predict residual stress and microstructure by thermo-plastic transient finite element simulation did not really begin until the early 1990s. These analyses, at Berkeley Nuclear Laboratories, initially used the BERSAFE system and later FEAT, essentially a computational fluid mechanics code with some solid mechanics added. Earlier European and North American work was taken as a guide. In particular, Ref.11-16) were taken as the inspiration for thermal modeling and used to establish appropriate techniques for deposition of the weld bead with appropriate spatial and temporal temperature profiles. Algorithms for phase transformation kinetics were taken directly from published work by Leblond and Devaux[17)], although this took place some years after a short period of collaboration between the CEGB BERSAFE development team and the then System TITUS team at Framatome during the planning of the UK's first and only pressurized water reactor at Sizewell B. The BERSAFE work in the 1990s was, however, preceded by a full 3-dimensional transient thermal analysis linked to an axisymmetric plasticity analysis in the late 1970s[18)].

Not surprisingly, some of the first UK welding simulations to be reported in detail were carried out at The Welding Institute (TWI). Two particularly valuable works were Ref.19,20). Unfortunately, these appear to be available only to industrial members of the Institute.

There is a significant body of work in the area of phase transformation, both from the UK and elsewhere, brought together through a series of international conferences on Numerical Methods in Thermal Problems organized by the University of Swansea in Wales throughout the 1980s. Some UK contributions include Ref.21,22), whilst the method for dealing with latent heat in the CEGB's BERSAFE system was described in Ref.23).

Finally, following the demand of nuclear industry during the end of 70^{th} and 90^{th} period, a considerable amount of research projects has been conducted to forecast the residual stresses in the welded components and in the weld itself. Surprisingly, no specific software had been derived from this experience, except in France where all participants of the nuclear program have built their own piece of software dedicated to the nuclear plants: EDF (the exploiting company), CEA (the government) and Framatome (the builder).

3. Expected Benefits of the Welding Process Simulation

The welding process induces micro-structural transformations, residual stresses and strains which play an important role on the in-service behavior or on the welding operation itself. Stresses and distortions are mainly due to temperature gradients and metallurgical transformations happening during the process. Thus the main benefits of a welding process simulation are:

- To test the feasibility of a welding process by trying different sequences and/or by checking the creation of gaps between parts.
- To evaluate the in-service behavior of structures in terms of strength, fatigue or stability.

If the feasibility of a welding process is related to the final distortions, then the full model including all the welds must be computed. Solutions can be found in changing the sequence and/or the clamping conditions.

To evaluate the mechanical strength, the microstructure and the residual stresses are necessary. But the lack of rules limit this kind of study to qualitative analysis (find the best solution among a set of trials). Attempts have been made to go further (see for example[24)]).

The risk of brittle fracture is greatly increased by tensile stresses, high triaxialities of stresses, and "hard" phases which can be located in the Heat Affected Zone (HAZ). Analyses can be made using fracture mechanics assuming the existence of a defect corresponding to a critical situation.

Fatigue life with a high number of cycles concerns the resistance to both the initiation of a defect and to its possible propagation under a cyclic loading. It depends on the number of cycles but also on the mean stress during those cycles. Welding residual stresses play an important role as they can increase the fatigue life if they are compressive and inversely if they are tensile. The Dang Van criterion for crack initiation is widely used in the automotive industry.

Hydrogen trapped in welds has a worsening effect on cracks appearing at low temperature (under 200°C). Diffusion–trapping models for hydrogen have been developed[25] and can be associated with criteria for crack initiation.

At high temperatures, during the solidification process in the mushy zone, cracks may also appear and are related to the viscoplastic behavior of the material.

Another range of industrial problems is the stability of thin welded structures. Compressive stresses and possible geometrical defects are the main reasons of such issues. For welded components, the full structure must be computed using a large displacement and large strains option.

So the analysis of welded components may require different kinds of computation. But, in all cases, microstructure, residual stresses and distortions are needed. The continuation of this paper is thus devoted to the analysis of the physical phenomena to simulate and to the numerical methods to use to reach this information.

4. Physical Phenomena Involved and their Modeling

The aim of this section is the study of the metallurgical and mechanical consequences induced by a welding operation. Only low alloy steels are regarded. The precise description of the phenomena involved in the heat input such as arc, material/laser interactions are beyond the scope of this paper as well as the analysis of fluid dynamics in the weld pool. From the thermo-mechanical point of view, the heat input can be seen as a volumic or surfacic energy distribution, and the fluid flow effect, which leads to homogenize the temperature in the molten area, can be simply taken into account by increasing the thermal conductivity over the fusion temperature.

The different phenomena involved and their couplings are given in **Fig.1**.

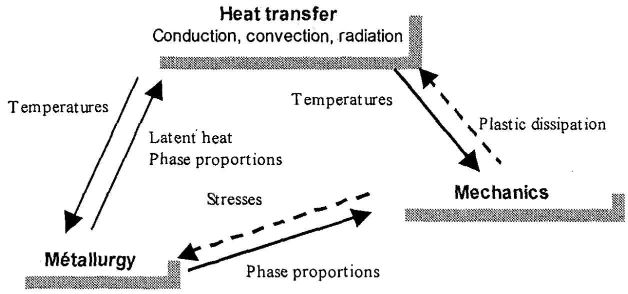


Fig.1 Physical phenomena involved and their couplings.

4.1 Heat transfer analysis

The heat transfer in solids are described by the heat equation[26]. The heat input can be represented either by an internal heat source or with a heat flux distribution. The double-ellipsoid heat source has been proposed by Goldak *et al.*[27] to model the heat input of processes with added material and medium energy processes. High energy processes such as electron beam welding or Laser welding vaporize the material and require another shape for heat input distribution. A gaussian volumic heat source within a cone has been often used successfully to model such processes. Other processes such as cladding with many electrodes can be modeled with gaussian surfacic heat sources. Finally, using one of those shapes or a combination of them, nearly all kind of processes can be computed.

But, the fitting of the shapes and of the input energy is a difficult task and most of the time, some experiments are needed to correlate the real and computed HAZ and/or the recordings of thermocouples.

When metallurgical transformations occur which is the case for standard steels, interactions between heat transfers and metallurgical transformations must be taken into account. Those interactions are:

- Metallurgical transformations depends on thermal history,
- Material properties depend on the phases,
- Phases transformations are accompanied by latent heats which have an impact on the temperature field.

Due to those interactions the heat transfer and the metallurgical analyses must be treated by a strong coupling formulation.

At each instant, a material is characterized by the proportions p_k ($\sum_{phases} p_k = 1$) of the different phases which compose it. From the modeling point of view, the phase proportions are additional state variables which evolution can be describe by standard differential equations on time as explained later. To account for the coupling between metallurgical transformations and material properties (thermal conductivity, density and enthalpy), a solution is to use a linear mixture rule from each phase individual properties[26].

The internal heating due to the plastic dissipation can be neglected considering the small transformation rates generated by a welding operation[28].

4.2 Metallurgical transformation models

For an hypoeutectoid steel, the main transformations to consider are the austenitic transformation during heating, and the ferritic, pearlitic, bainitic and martensitic transformations during cooling. Many approaches can be used to describe those transformations[29]. The models can be distinguished between two groups whether they are based on isothermal transformations (IT) diagrams or on Continuous Cooling transformation (CCT) diagrams.

To model isothermal transformation kinetics, the Johnson-Mehl-Avrami law is widely used. This law has been formerly proposed by Johnson and Mehl[30] and enhanced by Avrami[31] to describe the pearlitic transformation but is also used to describe ferritic and bainitic transformations. It can be written as:

$$p = 1 - \exp\left(-b\,t^n\right) \qquad (1)$$

where p is the phase proportion created and b, n, two parameters.

The martensitic transformation is time independent and consequently can be expressed as a function of the temperature only with the Koistinen-Marbürger law[32]:

$$p_M = p_A \cdot \left[1 - \exp\{-k(M_S - T)\}\right] \quad \text{for} \quad T \le M_S \qquad (2)$$

where p_A is the austenite proportion to be transformed, M_S, the temperature corresponding to the beginning of the transformation and k, a parameter.

In order to use those models for non-isothermal transformations, different approaches have been proposed by Inoue[33], and introduced in HEARTS, Reti *et al.*[34], Lusk *et al.*[35] or at INPL[36] and used in SYSWELD and FORGE2. Considering the model proposed by INPL, an anisothermal temperature evolution is decomposed into a succession of isothermal steps. Thus, in order to obtain the phase proportion p_{i+1} at time t_{i+1} (end of the $i+1^{th}$ step), the isothermal transformation kinetic at the temperature T_{i+1} is used. To do so, a fictitious time t^*_{i+1} corresponding to the time needed to generate the proportion p_i at temperature T_{i+1} is calculated first and the proportion p_{i+1} is then obtained using Eqn.(1) at time $t^*_{i+1} + \Delta t_{i+1}$.

This approach is used both for transformations occurring during cooling and austenitic transformation. For transformations during cooling, an incubation time is firstly computed using the Sheil's method. This model has been recently improved to account for the carbon content influence on the transformations kinetics[37].

In fact, the approaches using isothermal kinetics have been initially developed to model heat treatment processes. For the welding applications, the operating conditions always leads to fast cooling or heating rates. Consequently, models based on CCT diagrams have first appeared to be the most suitable ones. Generally, those models can be expressed with a differential equation of the following type:

$$\dot{p} = f(p, T, \ldots) \qquad (3)$$

Leblond and Devaux[17] suggested to use a simple first order differential equation:

$$\dot{p} = \frac{\overline{p}(T) - p}{\tau(T)} \qquad (4)$$

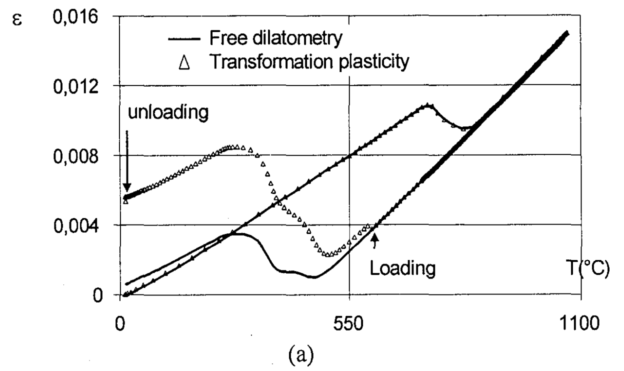
where $\overline{p}(T)$ and $\tau(T)$ are two parameters functions of temperature which are adjusted for each transformation in order to represent the CCT diagram. The full model also allows to compute the austenite grain size and its effect on the cooling transformation kinetics. This model has been extended to the case of more than one transformation with several phases. This model is the first one that has been introduced in SYSWELD. Equation (4) has been generalized later to reproduce the Johnson-Mehl-Avrami kinetics for isothermal transformations[17,38]:

$$\dot{p} = n.\frac{\overline{p} - p}{\tau}.\left(Ln\left(\frac{\overline{p}}{\overline{p} - p}\right)\right)^{\frac{n-1}{n}} \qquad (5)$$

The parameter identification requiring some efforts, a specific fitting method based on CCT or IT diagrams has been developed[38].

Based on CCT diagrams too, the model developed by Waeckel[39] and incorporated in ASTER and CASTEM 2000 softwares rests on an equation similar to Eqn.(3). The function f (of Eqn.(3)) has no explicit form but is computed at each point using information read on the CCT diagram. As a consequence, this model really sticks to the CCT diagram and cannot be used out of its boundaries, for example when the cooling rates exceeds the cooling rates of the diagram. However, the main advantage of this approach is that there is no need to identify parameters. For the austenitic transformation, Waeckel proposed to use Eqn.(4).

The modeling of the tempering is very important when residual stresses and distortions during a multipass welding operation are to be computed. Indeed, tempering effects result in the lowering of the yield stress of the material. In a multipass welding process, each pass generates a tempering effect on the HAZ induced by the previous weld beads. The consequences are very important on the residual stresses. The INPL[40] has proposed a dedicated model for the tempering of



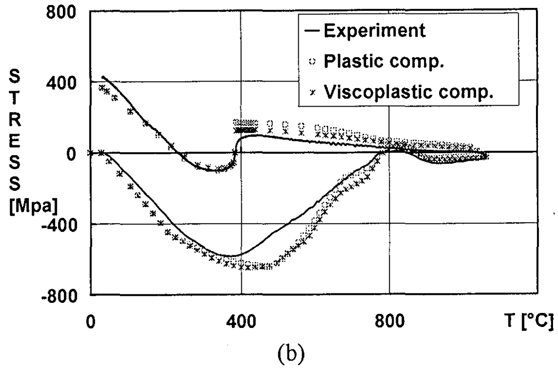


Fig.2 Free dilatometry test with transformation plasticity[44] and Satoh test[45].

martensite with three independent kinetics each of them using a Johnson-Mehl-Avrami law: precipitation of carbides in martensite, transformation of retained austenite into ferrite and cementite, transformation of carbides into cementite. Leblond, simply proposes to use Eqn.(4) to model pseudo-transformations from some as-quenched structure to a tempered one.

Finally, the effects of stresses on transformation kinetics have been widely examined by many authors[41,42]. Practically, the lack of material data is a strong limitation to the application of the models.

4.3 Mechanical analysis

The mechanical analysis is based on the usual equations describing the static equilibrium. According to the remarks of the previous section, this analysis can be uncoupled from the thermo-metallurgical analysis. Thus, the mechanical computation is achieved afterwards using temperature and metallurgical fields. The effects to consider are: the thermal strains, the volume changes due to the transformations (contraction during heating and expansion during cooling, **Fig.2(a)**), the influence of the phases on the behavior law (generally, the yield strength of phases are higher if they have been created with high cooling rates) and the transformation induced plasticity.

The volume changes due to transformations are a major cause of the residual stresses and strains appearance. To include those changes in a computation, a simple solution consists in changing the standard thermal strain into the following thermal and metallurgical strain:

$$\varepsilon^{th}(T) = \sum_{\text{Phases}} p_k . \varepsilon_k^{th}(T) \tag{6}$$

where ε_k^{th} represent the thermal strains of each individual phase. As shown in Fig.2(a), the ε_k^{th} differs not only by their slopes (which correspond to the heat expansion coefficients) but also by their values at the origin in order to reproduce the volume changes due to transformations[43]. The effect of the volume change occurring during a transformation on the residual stresses can be easily seen on a Satoh test (**Fig.2(b)**). This test, quite simple but difficult to control experimentally, consists in studying the evolution of the stress in a bar heated above the temperature corresponding to the end of the austenitic transformation (Ac3) and then cooled down. As expected, the stress at high temperature is close to zero. Then, at the beginning of the cooling period, tensile stresses reaching the yield strength are obtained. When the transformation proceeds, due to the volume change, a sudden stress reversal is observed leading to a compressive stress. It is clear that, as in the meantime the specimen continue shrinking, the stress value and the sign at the end of the transformation strongly depend on the temperature start of the transformation, its range and the new phase volume condition.

As soon as one considers the behavior of steels during transformation, a very important phenomenon to take into account is the transformation induced plasticity (Fig.2(a)). The transformation plasticity effect can be shown using a combined dilatometry test applying a stress when the transformation during cooling proceeds. In that case, a small stress (small compared to the yield strength of the weakest phase of the material at that time) applied during the transformation while cooling will generate a residual strain nearly proportional to the applied stress. This behavior can be associated with two mechanisms. The most important is the Greenwood-Johnson mechanism[46] which states that the volume change during the transformation is enough to induce plasticity in the weakest phase (austenite). Those small strains are orientated in the direction of the applied stress. The Magee mechanism[47] is related only to martensitic transformation and is the result of the orientation of the martensite needles during the transformation by the stress state. But, except for memory-shape alloys for which this phenomenon is the only present, Magee mechanism can be often neglected.

Transformation induced plasticity has been studied by many authors[46-51]. Different models have been investigated to account for the Greenwood-Johnson mechanism. All the models can be written in the following form in a three-dimensional case:

$$\dot{\boldsymbol{\varepsilon}}^{pt} = \frac{3}{2} K \, \mathbf{s} \, f'(p) \, \dot{p} \tag{7}$$

where $\mathbf{s}$ is the stress deviator and K, a material parameter.

Among all the models dealing with the behavior of steels during transformation, the model proposed by Leblond and coworkers[52], based on a micro-mechanical analysis, is widely used. It can be found for example in SYSWELD and ASTER.

Leblond and coworkers assume that elasticity constants are the same for all the phases and prove that the plastic strain rate can be expressed in the following form[43]:

$$\dot{\boldsymbol{\varepsilon}}^{p} = a(\ldots)\dot{\boldsymbol{\sigma}} + \mathbf{b}(\ldots)\dot{T} + \mathbf{c}(\ldots)\dot{p} \tag{8}$$

Mathematical expressions for the different implied functions have been derived from the micro-mechanical analysis and elementary finite element analyses. Perfectly plastic phases have been first considered. Hardening phenomena (isotropic and kinematic) have been introduced later. So, for transformation plasticity, Leblond and coworkers have obtained[52]:

$$K = \frac{2}{3\sigma_{\gamma}^{y}} \frac{\Delta V}{V} \qquad f(p) = p - p \log p \tag{9}$$

where $\Delta V / V$ represents the relative volume variation during the transformation and σ_{γ}^{y}, the austenite yield strength. Recently, these expressions have been slightly improved for small values of p by Taleb and Sidoroff[53].

The viscoplastic effects have been neglected for a while arguing that welding processes only involve very short times. But, the mechanical properties of austenite at high temperatures depend strongly on the strain rate and these properties have an important effect on the final residual distortions[54]. Therefore, this effect must be integrated in the models. Moreover, an experiment representative of a welding operation developed at INSA (Lyon, France) has pointed out that viscoplastic effects cannot be neglected any longer[45,55]. Wang and Inoue[56] present a model which makes no exception for the transformation plasticity. At INPL (see for example[57]) an elastic-viscoplastic model with combined hardening has been developed. The yield strength and the viscous parameters are obtained with mixture laws. Videau *et al.*[58] have proposed a non-unified elastic-viscoplastic model integrated in ZeBuLoN. Coret and Combescure[59] propose a parallel model in CASTEM 2000. The strain is assumed identical in all the phases and the macroscopic stress is obtained with a mixture law on the individual stresses in each phase. Finally, Bergheau *et al.*[60] have generalized to viscoplasticity the model proposed by Leblond by considering the yield stress of the phases as a function of the viscoplastic strain rate.

5. Computation Methods

5.1 Transient analysis

The finite element method is well adapted to the computation of residual stresses and strains due to welding processes. As previously explained, a welding process computation can be split into two steps. First, the temperature and phases evolution are determined as a function of time. The temperature field is obtained at nodes whereas the phase proportions are calculated at the integration points of the elements. Then, the mechanical computation uses the previous results to get displacements (at nodes) and stresses (at integration points). Generally, for practical reasons, the mesh used for the heat transfer computation is also the one used for the mechanical analysis. Some softwares have an activation/deactivation procedure of elements which allows to model the added material if necessary (ANSYS, SYSWELD for example). However, the main difficulty comes from the extremely high gradients around the heat source for the temperature and consequently for the stresses. This heat source is moving and the mesh must be refined along the weld path leading to very large finite element models. In most cases, the computation time for industrial parts are unacceptable with the usual projects planning. Other methodologies must be investigated depending on the expected results.

A first approach is to use two-dimensional models. Generally, a section perpendicular to the welding direction is used with a plane strain or generalized plan strain assumption for longitudinal welds. For tubular structures, an axisymmetric hypothesis is used. Transverse stresses in the meshed plane are generally correct compared to the experiments but the out of plane stress is overestimated especially for longitudinal welds because of the plane strain hypothesis. Using an axisymmetric hypothesis means that the weld is done all over the part at the same time. In this case, the evolution of gap during the welding and the evolution of the clamping conditions due to the weld solidification are not accounted for leading generally to high disappearances in residual distortions. Only a three-dimensional simulation can give proper results.

One solution to reduce the number of elements of the model is to use an adaptive meshing procedure[61,62]. This approach consists in refining the mesh around the heat source where the gradients are high and unrefining

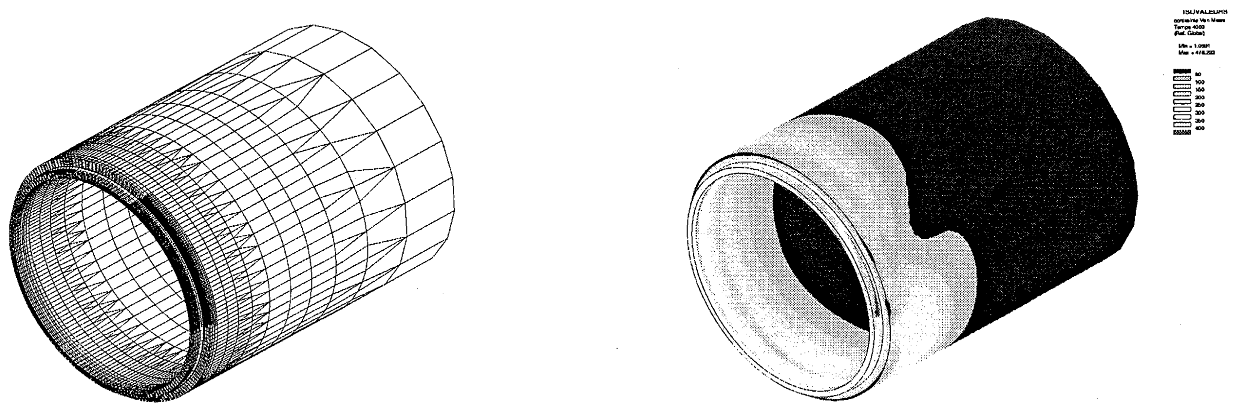


Fig.3 3D Multipass welding simulation with adaptive meshing (mesh and von Mises stresses) (courtesy of Framatome ANP).

it when the heat source has moved - that is when gradients are lower - (**Fig.3**). This methodology requires specific software developments, first to ensure the elements compatibility between the refined mesh and the initial mesh, second to transfer the results from the initial mesh to the refined one and after from the refined one to the initial one.

If the part can be modeled with shell elements, the previous approach can be generalized using solid elements only around the welding path (limiting the model size and improving the bending behavior of the model).

Anyway, such approaches remain expensive in term of computational efforts and in order to treat many joints on large structures, other assumptions must be made.

5.2 Steady state computation

In most cases, temperature, metallurgical and mechanical fields are quasi-stationary on the main length of the weld path. Different authors[63,64)] have proposed numerical formulations to solve this problem in a moving reference frame attached to the heat source. When possible, this method gives many advantages. First, the heat source is fixed and the mesh has to be refined only around its location and not anymore along the full weld path. Secondly, only one computation step is necessary to obtain the steady state solution. The exhaust of the torch (if end effects are needed) can be also computed with a transient analysis limited to a small part of the weld path.

5.3 Local/global approach

An interesting solution to determine distortions in large structures within an acceptable amount of computation time is to make the simulation in two steps[65-67)]: a local step to treat the welding effects around the weld on a limited area and a global step to compute the full structure using the first step results.

The plastic strains induced by a welding operation are limited to the vicinity of the weld path. It is assumed that those strains are related to the local thermal and mechanical conditions. Under this assumption, a three-dimensional local model including the physical effects described previously will provide a correct representation of a real weld. Then, the local plastic strains can be injected as initial strains in the whole structure. This global model can be used to obtain the distortions or to study the behavior of the assembly during the welding sequence. A new technology has been recently proposed by Souloumiac *et al.*[67)] to transfer the local results to a global model made of shell elements.

The main difficulty with this method is that the local model must reflect properly the boundary conditions of the global structure. Some engineering is needed for this step. However, this methodology allows to use coarse meshes which make the welding process simulation feasible on large structures. Moreover, the welding sequence can be computed and optimized to limit the final distortions and/or the parts matching due to gaps creation issues.

6. Applications

6.1 Multipass welding

This simulation, rather old as done in 1988, is a very interesting demonstration of the metallurgical and mechanical consequences induced by successive deposits of material. The treated case is a filling operation. The base metal is a low alloyed carbon steel 16MND5. A two-dimensional plane strain model has been done in a plane perpendicular to the welding direction.

In **Fig.4**, as-quenched martensite proportions and longitudinal stresses are plot after one and three deposits. A pseudo-transformation has been defined between as-quenched and tempered martensites. The HAZ can be clearly seen in Fig.4. After the third deposit, a high

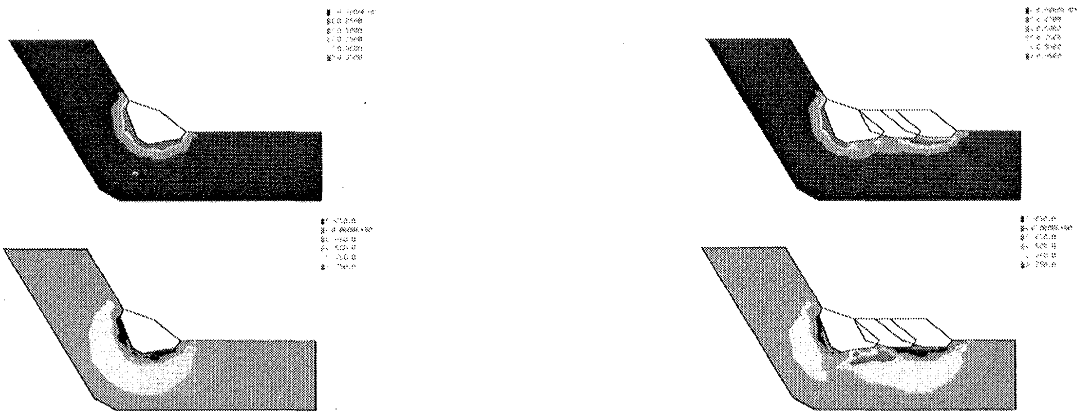


Fig.4 Multipass welding (up: as-quenched martensite proportions, down : longitudinal stresses) (courtesy Framatome ANP).

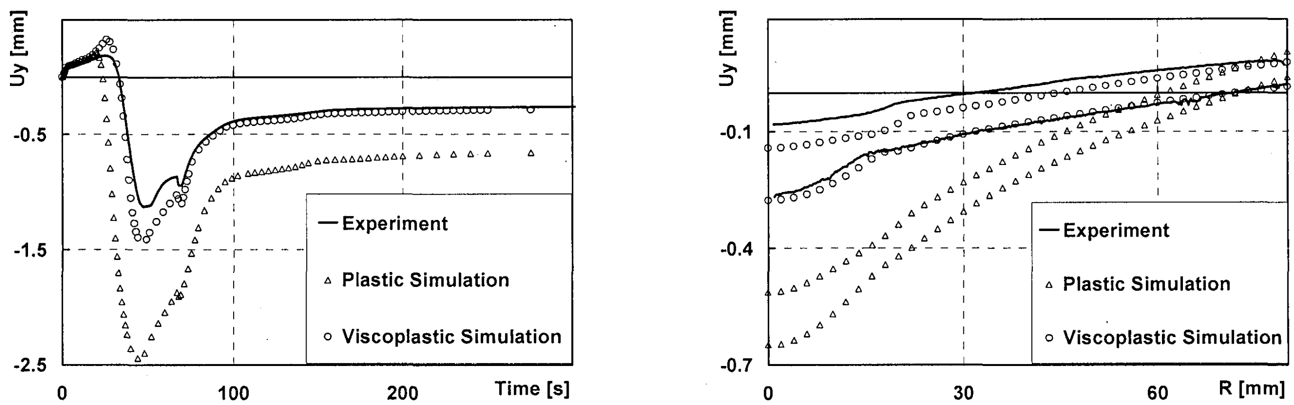


Fig.5 Residual strains of the disc[60].

tensile stress area appears next to the HAZ of the third deposit. There lies the tempered martensite as shown by the metallurgy plot at the same time. The lowering of the yield strength in this area concentrates the tensile stresses needed to equilibrate the structure leading to dramatically high stresses. This example gives a good illustration of the gradients existing in welds and of the importance of metallurgical consequences.

6.2 INZAT experiment

This experiment has been developed by INSA Lyon in order to validate the different models and assumptions used in softwares. This experiment has been developed in a collaborative program implying Rhône-Alpes laboratories and nuclear related organisms and companies. It consists in a disc heated in its center with a CO_2 laser. By doing so, axisymmetric computations can be achieved. Different thicknesses and different kind of loading have been considered[55,68]. Temperatures and axial displacements can be recorded during al the duration of the experiments. Afterwards, stresses can be measured using X-Ray diffraction. Strain measures using an image correlation method and microstructure analyses can also be performed.

The experiment discussed here concerns a disc of 160 mm diameter with a 5 mm thickness made of a 16MND5 steel. The heat input is calibrated in order to obtain an austenitic structure in the central area of the disc. Both elastic-plastic and elastic-viscoplastic computations have been performed using the models of Leblond and coworkers[43,52,60]. The experimental results in terms of residual distortions can be correlated only with the model including the viscous effects (**Fig.5**). Similar results have been obtained by Coret[59].

6.3 Residual distortions of a ship structure

The case detailed here concerns the influence of the welding sequence on the final distortion of a ship structure. This work has been done during the BRITE-EURAM European project « Integration design environment and numerical analysis of production processes » (D-SIGN).

The structure considered is a large structure from the simulation point of view; its overall dimension is about 2,50 m. The objective is to validate the local-global approach described previously. The two welding sequences are shown in **Fig.6**. The welding is done using a CO_2 laser. The thermal model accounts for the keyhole

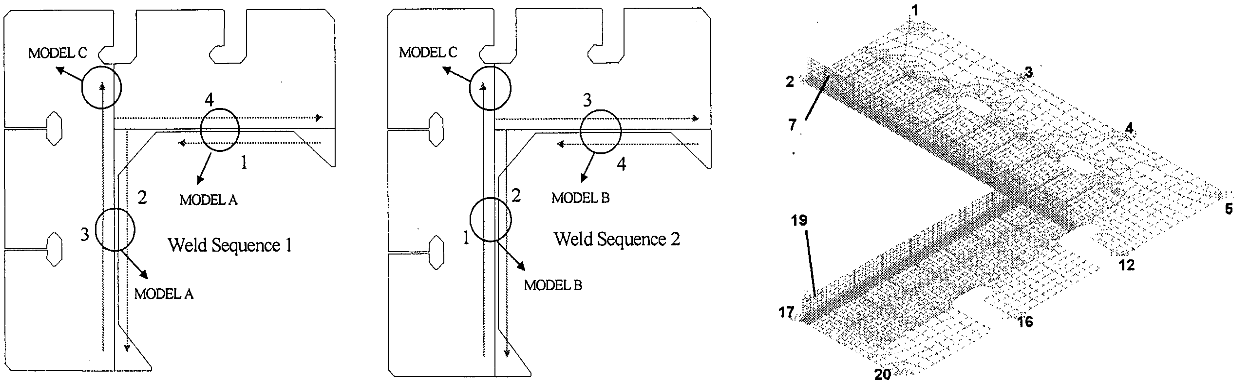


Fig.6 Definition of sequences and points of measurement[69].

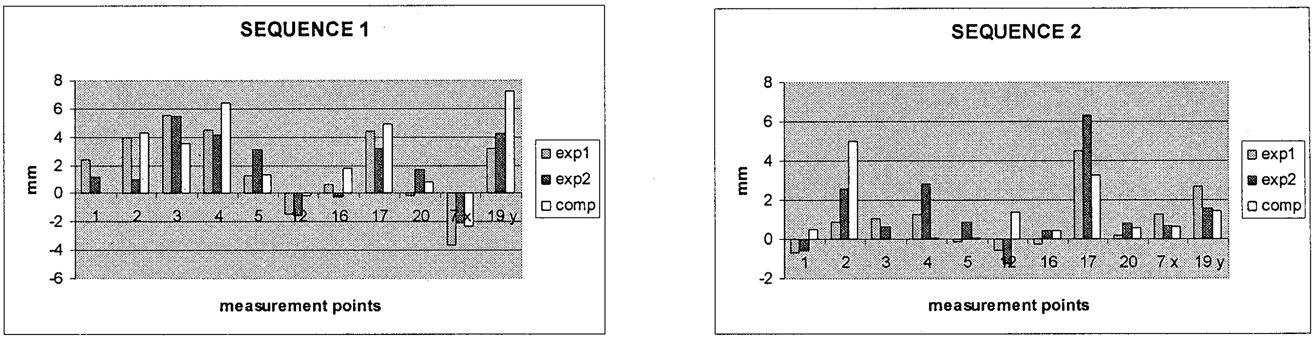


Fig.7 Measured and computed residual distortions[69].

which shape and size have been determined using the PHYSICA software. The local and global computations have been performed with SYSWELD[69]. The final distortions (vertical displacements) have been compared with experimental results in **Fig.7**. The agreement is very good especially for sequence 1 and it confirms the capability of this method to compute residual distortions in large structures.

7. Conclusion

The numerical simulation of welding is a domain which is not limited anymore to research centers and is now used in industry during the design and/or production stages. Generally, such computations are done with general purpose finite element softwares or dedicated softwares such as SYSWELD.

In term of expected results, the existing methods have been validated in term of microstructure and residual stresses. The reason is that the material data knowledge has been really improved in the last decade and that local models are generally sufficient to obtain acceptable results. The next frontier in that domain is the determination of criteria and rules to quantify the weld acceptance levels.

As concerns the distortions, the computation power is not sufficient to treat industrial problems with a full transient scheme and simplified method have been developed and validated. The efforts in the future are to define precisely the limits of the simplified methods and, if possible, to improve the material databases at high temperature which have an influence on the final shape.

Finally, it is certain now that the welding simulation has entered in the industry world and that it will be more and more often a new actor in the decision process.

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