TENSILE CHARACTERIZATION OF A BIMETALLIC WELD (BETWEEN MARTENSITIC AND AUTENITIC STEELS) WITH A NEW MEASUREMENT SYSTEM FOR TENSILE TESTING

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ABSTRACT

Mod 9Cr-1Mo steel (T91) is a candidate material for steam generator of SFR (Sodium Fast Reactors). In order to validate this choice, it is necessary, firstly to verify that it is able to withstand the planned environmental and operating conditions, and secondly to check if it is covered by the existing design codes, concerning its procurement, fabrication, welding, examination methods and mechanical design rules. A large R&D program on mod 9Cr-1Mo steel has been undertaken at CEA in order to characterize the behavior of this material and of its welded junctions.
In this frame, a new measurement system for tensile testing was developed in the LISN laboratory of the CEA (French atomic commission), in order to characterize the local behavior of the material during a whole tensile testing. Indeed, with the conventional measurement system (typically an extensometer), the local behavior of the material can only be determinate during the stable step of the testing. So, usually the behavior of the material during the necking step of the step is unknown.
This new measurement is based on the use of some laser micrometers which allow measuring the minimum diameter of the specimen and the curvature radius during the necking phase with a great precision. Thanks to the Bridgman formula, we can evaluate the local behavior of the material until the failure of the specimen.
This new system was used to characterize the tensile propriety of a bimetallic welded junction of Mod 9Cr-1Mo steel and austenitic stainless steel 316L(N) realized with GTAW process and inconel filler metal.
These works lead to propose a tensile curve for each materials of the welded junction.

INTRODUCTION

Mod 9Cr-1Mo steel (T91) is a candidate material for steam generator of SFR (Sodium Fast Reactors). In order to validate this choice, it is necessary, firstly to verify that it is able to withstand the planned environmental and operating conditions, and secondly to check if it is covered by the existing design codes, concerning its procurement, fabrication, welding, examination methods and mechanical design rules. A large R&D program on mod 9Cr-1Mo steel has been undertaken at CEA in order to characterize the behavior of this material and of its welded junctions.

The characterization of the ductility is based on standard tensile test. This test is characterized by two phases:

- The first phase corresponds to a uniform decrease of the section of the specimen and to an increase of the load. This phase is called stable phase (figure 1.). During this phase the determination of the stress and the strain can easily be done with conventional measurement system.
- During the second phase, the strain in the specimen is not uniform. We can see a quick localization of the strain in the specimen and an important decrease of the load. This phase is called unstable phase or necking. During this phase the determination of the strain and the stress are difficult and cannot be done with conventional measurement system.

In the same way, the characterization of the behavior of different materials of a weld junction is delicate: the geometry of the weld does not allow machining homogeneous conventional specimen. So the specimen is composed of different material with different mechanical properties. When the tensile test begins, we can see generally rapidly that the strain is not uniform in the specimen (figure 2) and so classical method cannot be applied.

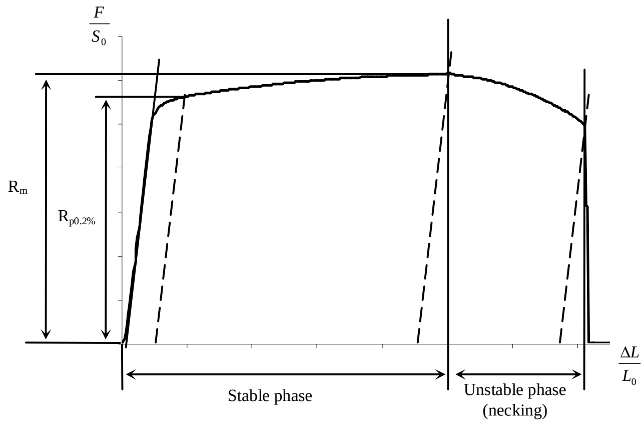


Figure 1: stable and unstable phase's definition for a tensile test

In this frame, a new measurement system for tensile testing was developed in the LISN laboratory of the CEA (French atomic commission), in order to characterize the local behavior of the material during a whole tensile testing and to characterize the material of a weld junction.

At first, this paper presents the new measurement system and the linked analyses.

Then, the experimental program is described and the results are presented.

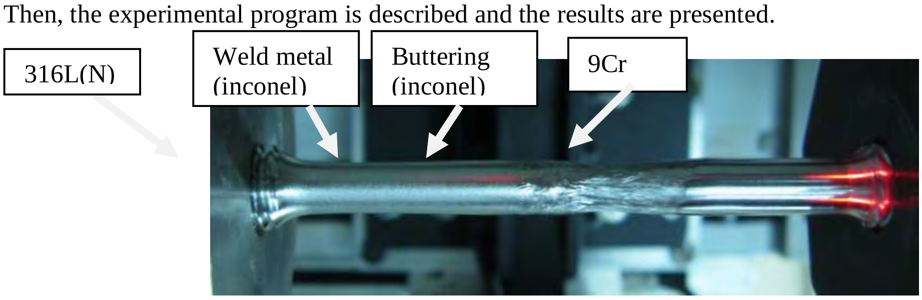


Figure 2: stable and unstable phase's definition for a tensile test

DESCRIPTION OF THE NEW SYSTEM MEASUREMENT

In the stable part of the testing (figure 1) the strain and the stress are calculated with the conventional methods:

- The elongation is calculated with the displacement imposed (a correction is applied to take into account the compliance of the testing facility).

$$e = \frac{\Delta l}{l_0} \qquad (1)$$

The strain is deduced by the following formula

$$\varepsilon = \ln(1+e) = \ln(1+\frac{\Delta l}{l_0}) \qquad (2)$$

- The conventional stress is calculated with the quation (3)

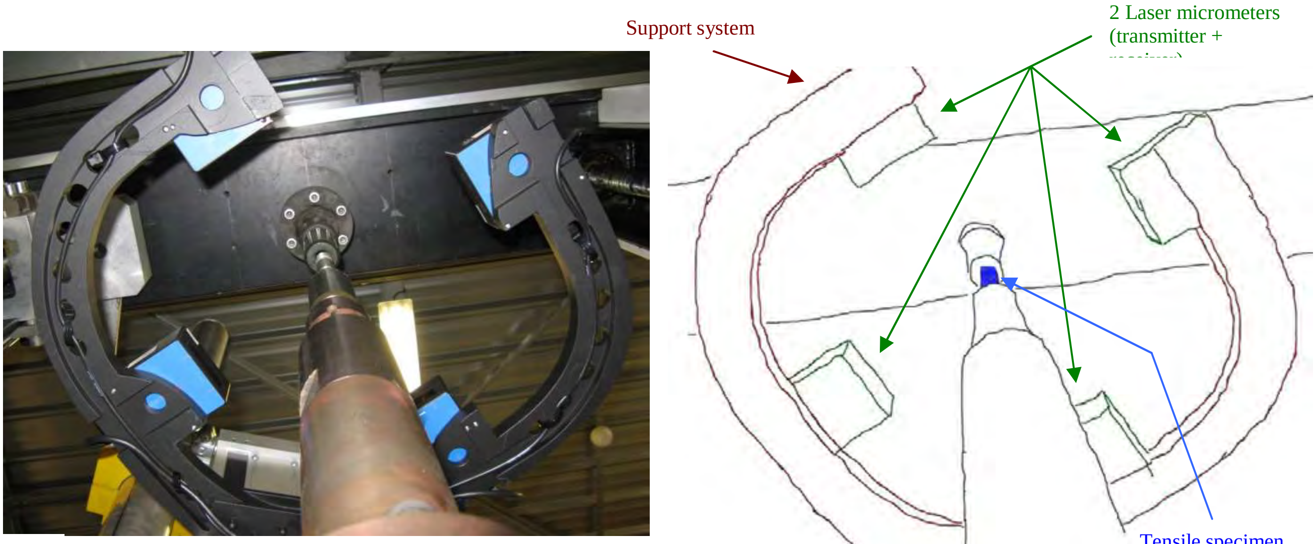
$$\varepsilon = \ln(1+e) = \ln(1+\frac{\Delta l}{l_0}) \qquad (3)$$

The true stress is deduced with the formula (4)

$$\sigma_{true} = \sigma_{conv}.(1+e) = \sigma_{conv}.(1+\frac{\Delta l}{l_0}) \quad (4)$$

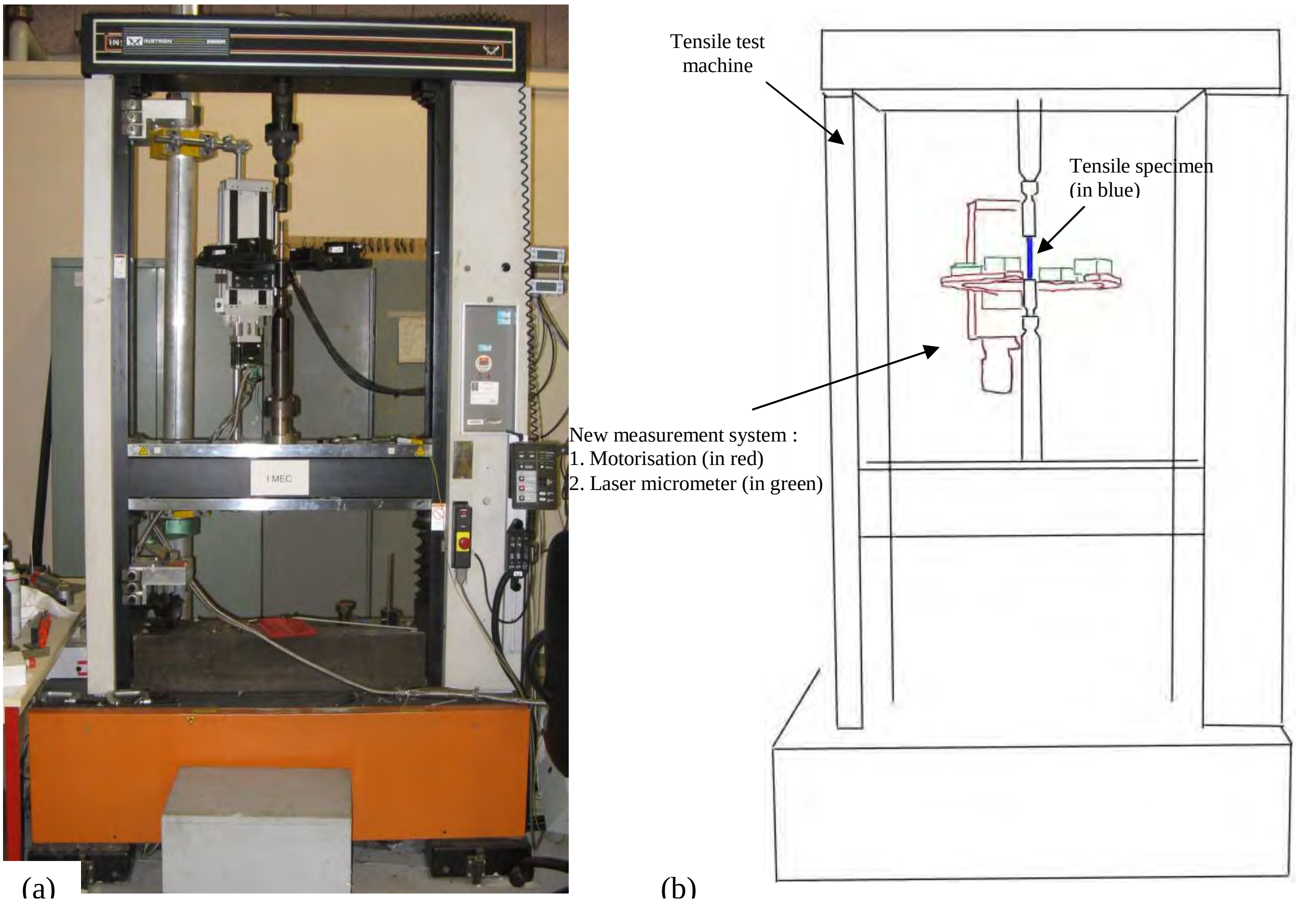
However these formula are not available when the section of the specimen is not uniform. Another method must be used during the necking. When the load reached its maximum, the instability phase begins and so the stress state is no longer uniaxial and the plastic strain is not homogeneous in the specimen.

It is why we have developed a new system measurement for tensile test.



(a) (b)

Figure 3: Bottom view of the system of measurement: (a) picture – (b) schematic diagram



(a) (b)

Figure 4: Description of the test utilities: (a) picture – (b) schematic diagram

The new measurement system is adapted on a electromechanic testing machine which is usually used for tensile test This system is composed of two main parts:

- Two High precision laser micrometers. (in green in the figures 3 and 4) A micrometer is a laser-based measuring system with integrated high resolution CCD camera. The ThruBeam micrometer measures the dimension of an object or the position of an edge by using the shadow-casting principle. These micrometers measured the diameter of the tensile specimen in two directions. The use of two micrometers placed perpendicular allows studying the orthotropic material.
- The motorization system (in red in the figure 3 and 4). It moves periodically and quickly the laser micrometers following the tensile axe in order to obtain a complete profilometry or 'scan' of the tensile specimen.

For each scan, we can determine:

- the smallest diameter in the calibrated part of the specimen noted 2a in the figure 5. Neglecting the elastic strain, the local strain in the necking zone can be calculated as follow

$$\varepsilon \approx -2.\ln\left(\frac{a}{a_0}\right) \qquad (5)$$

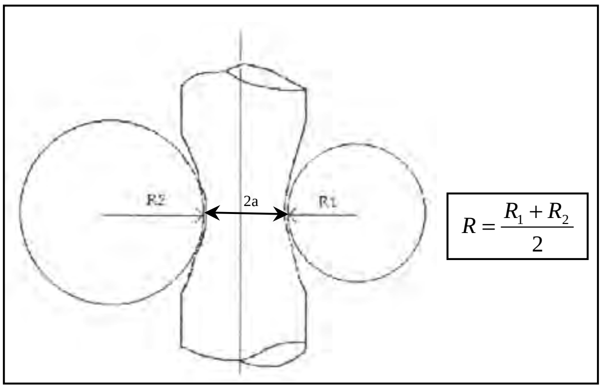


Figure 5: Definition of 2a and R

- When the load reached its maximum, the instability phase begins and so the stress state is no longer uniaxial. To take into account the multiaxiality, Bridgman [1] proposes the following equation

(6)

where R is the radius curvature and   is the minimal section in the necking zone.

For that, a specific program was written to analyze the scan and determine the radius curvature R. For each scan the minus radius 'a' in the necking zone is detected. A selection of N points in the vicinity of this point is selected and a polynomial adjustment r(z) is carried out (figure 6). The curvature radius is then given by the formula (7).

$$R = \frac{\left(1 + \left(r'(z)\right)^2\right)^{3/2}}{r''(z)} \qquad (7)$$

In order to have a good calculation of R, different number of selected points N and different powers of polynomial adjustment are used.

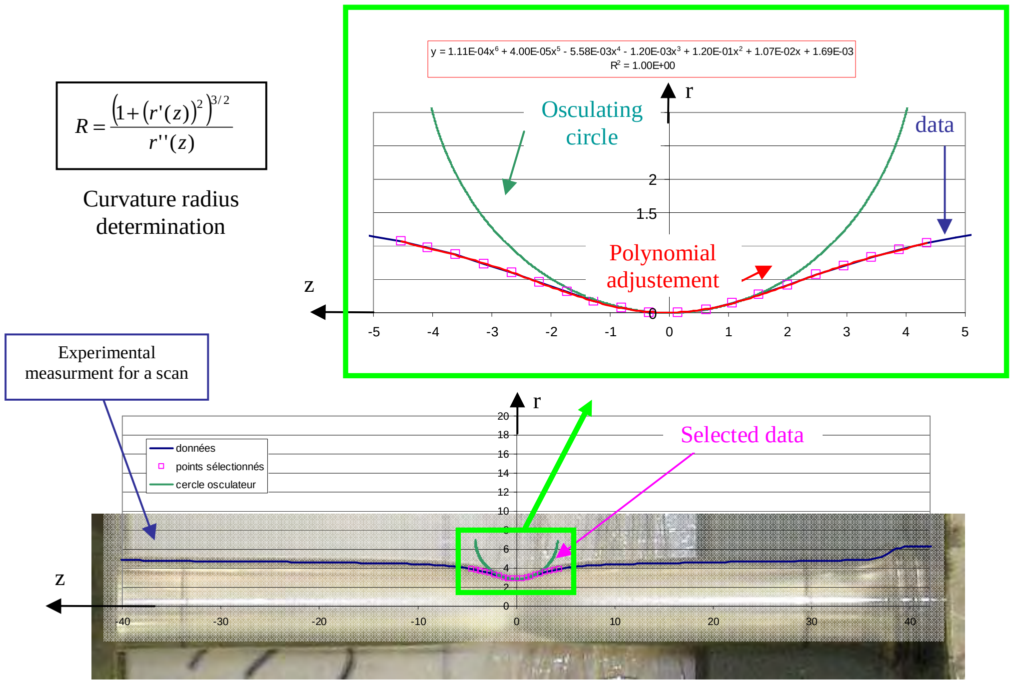


Figure 6: Determination of the curvature radius R

PRESENTATION OF EXPERIMENTAL TESTING ON SMOOTH SPECIMEN

Characterization of base, buttering and weld metal

In order to characterize the base metal (316L(N) and 9Cr), 2 specimen were machined (annex A) far from the weld. To characterize the weld and buttering metal in the longitudinal direction, 2 specimens were machined so that the specimen is homogeneous in the longitudinal direction of the weld (figure 7). Finally, 2 specimens through the weld have been machined, named crossweld specimen. These specimens contain all the metallurgical parts of the welded junction (figure 9).

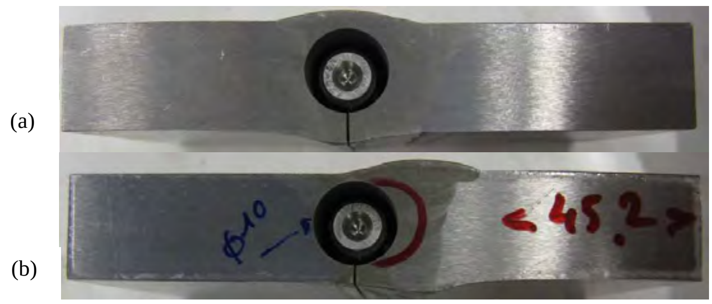


Figure 7: Machining of specimen in the weld (a) and the buttering (b) metal

The figure 8 presents the conventional curves for the 6 specimens. We can observe the large difference of behavior between the 2 base metal 9Cr steel and 316L(N). The austenitic steel 316L(N) is characterized by a large ductility and a small yield strength. At the opposite, the 9Cr steel presents a small ductility and large yield strength. The weld and the buttering metal have similar mechanical behavior which is halfway between the behavior of the 2 base metal.

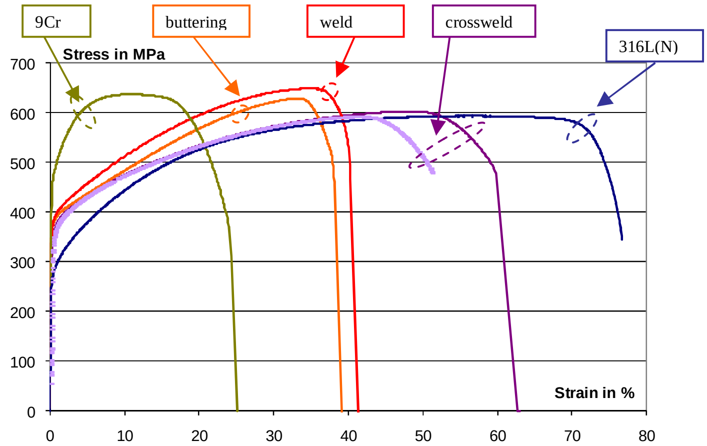


Figure 8: Conventional curves

The curves corresponding to crossweld specimens are also presented. It must be précised that the conventional strain are deduced from the testing displacement of the machine and so it corresponds to the cumulated strain of all the metallurgical parts of the weld. As it can be saw in the figure 9, the strain is not uniform along the specimen. However the conventional curve shows some informations:

- The yield strength is near for yield strength of the buttering and meld metal,
- The ultimate stress is similar to 316L(N) ultimate strength.

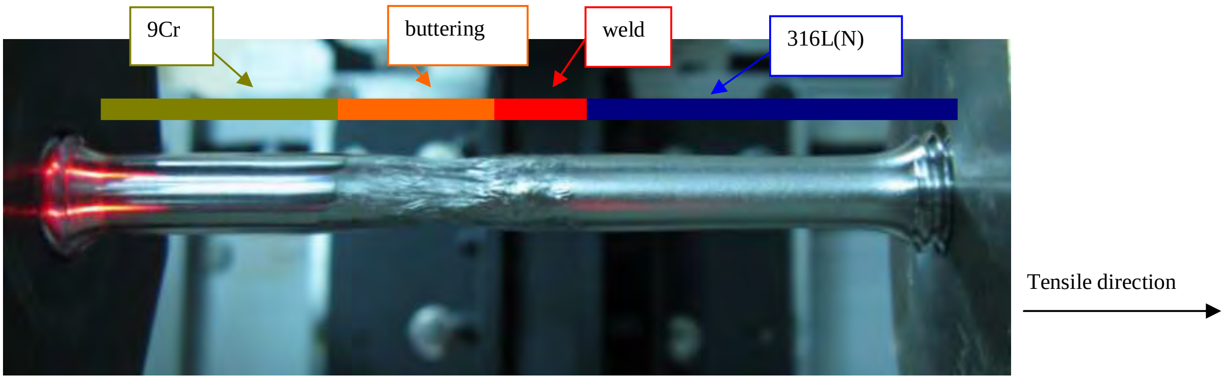


Figure 9: Picture of a test on crossweld specimen

Thanks to the profilometry measurement, we can observe the evolution of the geometry of the specimen which is specially interesting for such crossweld specimen. The figure 10 presents some profilometry measurement during a test on crossweld specimen.

We can observe the localization of the strain in the 316L(N) and buttering parts of the specimen at the onset of the plasticity (blue curve in the figure 10). At the contrary, the hardest part of the specimen in 9Cr steel does not present deformation. After, with the increase of the load, all the parts of the specimen are deformed but the 316L(N) and the buttering present the most important strain (pink and green curve). Finally, we observe a localization in the buttering when the ultimate load is reached.

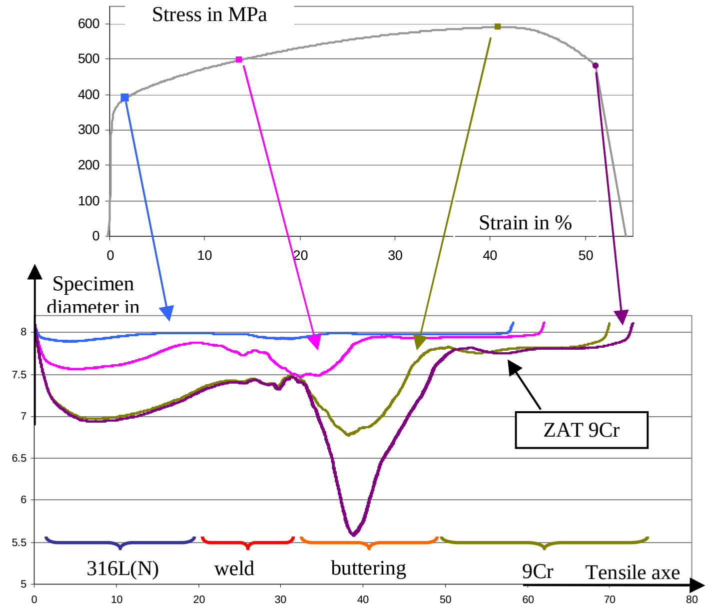


Figure 10: Examples of profilometries measurement during a tensile test on crossweld specimen.

As it was described in the paragraph 2, it is possible to determine the behavior of the material until the failure of the specimen thanks to Bridgman formula. The figure 11 shows tha application of these equation for the 2 tests on the 316L(N) and 9Cr specimens. The application of Bridgman equations allows considerably increases the known of the behavior of the material. For example, the behavior 9Cr is determinate until a strain of 130% while the conventional method cannot determinate the behavior up to 10% corresponding to the apparition of the necking.

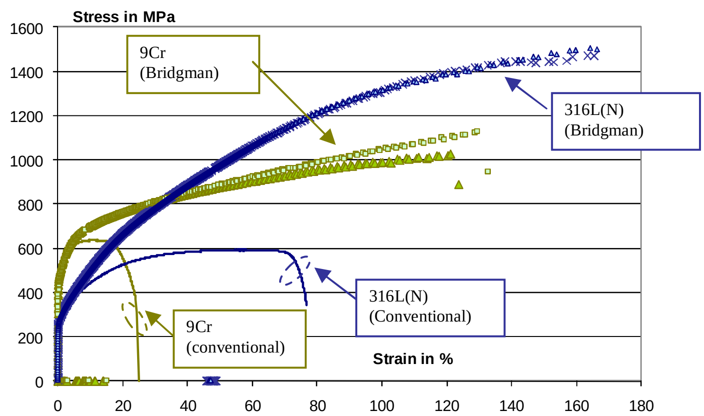


Figure 11: Application of Bridgman formula for 316L(N) and 9Cr steel.

In the same way the figure 12, the Bridgman methodology was applied on buttering and weld metal specimen.

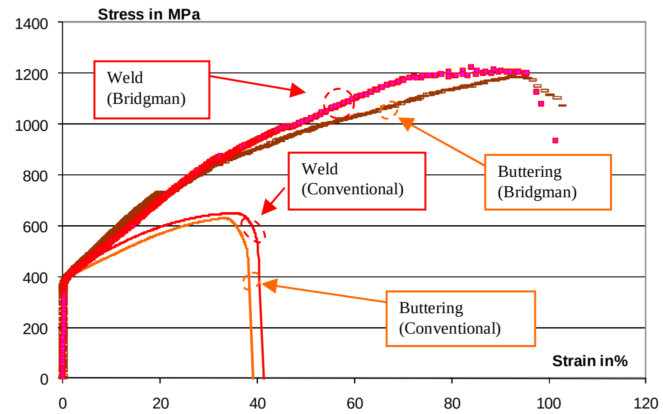


Figure 12: Application of Bridgman formula for weld and the buttering steel.

The figure 13 presents the application of the Bridgman methodology for the 2 tests on crossweld specimens. We can show that the 'Bridgman curve' obtained is very near from the curve of the buttering and the weld metal while the conventional curves are different. But in this case, the conventional curve is difficult to analyze because the calculation of the strain corresponds to a mix of the strain of the different material of the weld. For the 'Bridgman curve', the strain is determined only with the minimum diameter of the specimen which is located in the buttering for the crossweld tests. So this new measurement system allows determining the behavior of the softest material of the weld.

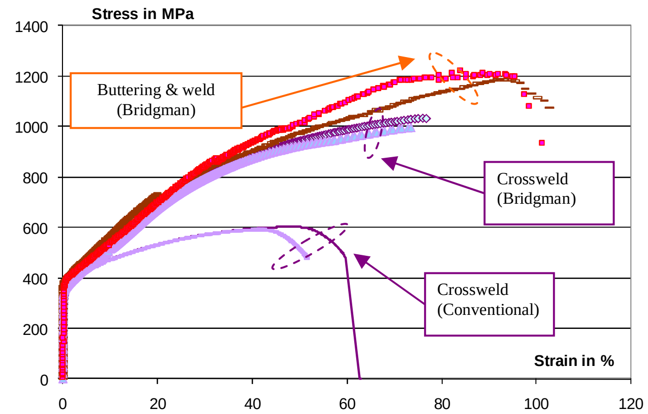


Figure 13: Application of Bridgman formula for crossweld specimen.

VALIDATION OF THE METHOD

To valid the method and the behavior calculated, we propose to perform a finite element modeling of the tensile test with the Cast3m [2] software.
The mesh used for this modeling and the associated boundary conditions are presented in the figure 14. The boundary conditions are as following:

- The displacements of the line AB are locked.
- The line AC is the axisymetric axe.
- The loading displacement is imposed on the line CD.

The modelling is 2D with axisymetric calculation option with quadratic element QUA8.

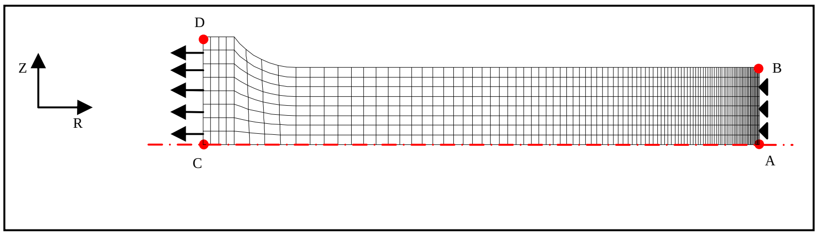


Figure 14: Boundary conditions

In numerical simulations conducted in this study, the material is assumed isotropic elastic plastic. In this context, the behaviour of elastic material is given by Hooke's law and the yield criterion is adopted as the criterion of Von Mises. So the material behaviour used in this modelling correspond to the material behaviour determined experimentally i.e. the curves named ‘Bridgman’ in the figures 11 & 12.
All calculations were performed assuming large strains and large displacements. In this context, the geometry of the structure is updated at each calculation step (the stiffness matrix is recalculated at each step).
This assumption is made compulsory by the very large strains observed during the tensile tests that affect significantly the geometry of the specimen. These changes in geometry that affect the test itself (loss of the load during unstable phase), it is imperative to make this assumption to model the phase of necking. Recall that the stricture is not due to the weakening of the material but is a consequence of shape change during the tensile test.
Given the large strains (well above 10%), were also retained the assumption of large strains. The current version of CAST3M offers two derivatives in the objective law of behavior: the derivative of use Truesdell and Jaumann derivative. The Jaumann derivative is more sensitive to the influence of the time step. Therefore we chose to Truesdell derivative of the calculations (derived the default in cast3m software).

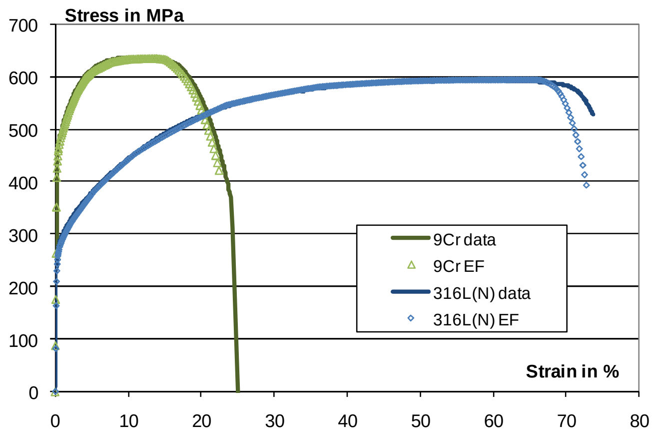


Figure 15: Comparison of numerical and experimental evolution of conventional stress in function of elongation for 316L(N) and 9Cr tests

Figure 15 compares the experimental and numerical evolution of conventional stress in function of elongation for the tests on base metal 316L(N) and 9Cr steels. We can see that the modeling allows very well reproducing the experimental data.
Figure 16 compares the experimental and numerical evolution of conventional stress in function of elongation for the tests on weld and buttering metal. Here too, we see a very good accordance between the numerical and the experimental data.

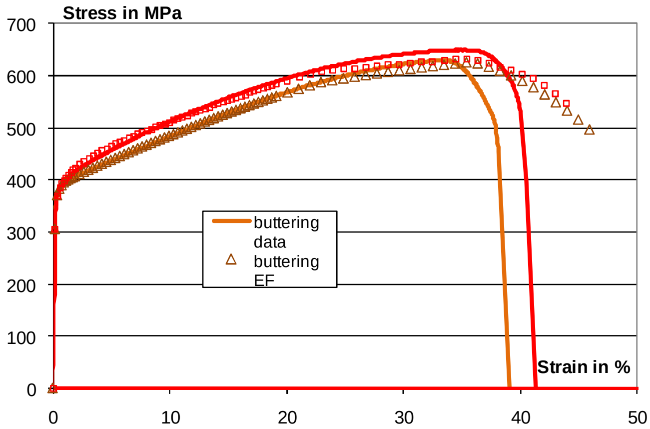


Figure 16: Comparison of numerical and experimental evolution of radius curvature in function of strain

These two results valid the new system measurement and the methodology used.

CONCLUSION

Mod 9Cr-1Mo steel (T91) is a candidate material for steam generator of SFR (Sodium Fast Reactors). In order to validate this choice, it is necessary, firstly to verify that it is able to withstand the planned environmental and operating conditions, and secondly to check if it is covered by the existing design codes, concerning its procurement, fabrication, welding, examination methods and mechanical design rules. A large R&D program on mod 9Cr-1Mo steel has been undertaken at CEA in order to characterize the behavior of this material and of its welded junctions.

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These works lead to propose a tensile curve for each materials of the welded junction.

A ‘classical’ tensile test on crossweld specimen was also realized. On such test, the localization of the strain appears at the onset of the plasticity in the softest material. The application of the Bridgman methodology allows characterizing this material.

REFERENCES

[1] « Studies in Large Plastic Flow and Fracture ». PW Bridgman. MC Graw-Hill. New York (1952).

[2] http://www-cast3m.cea.fr/

Annex A
Cutting drawing

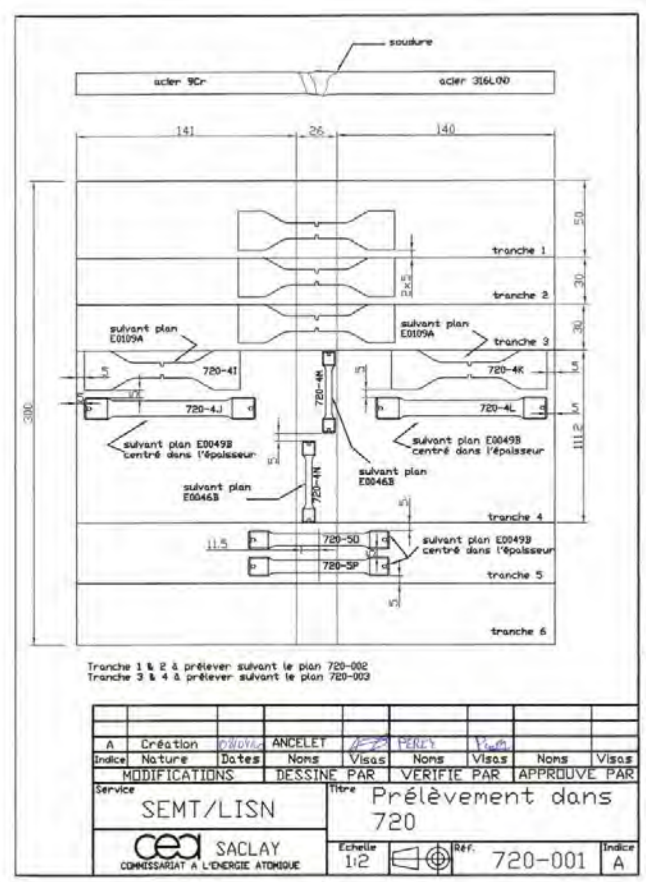

Figure A1: cutting drawing