Application of a second-gradient model of ductile fracture on a Dissimilar Metal Weld

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Abstract. A "micromorphic", second-gradient model applicable to ductile porous materials has been proposed, as an improvement from the fundamental work of Gurson that take into account the physical mechanisms responsible for ductile damage. The model has been applied to the study of fracture of the decarburized layer of a Dissimilar Metal Weld. The model successfully reproduces the crack path experimentally observed in a notched tensile sample extracted from this weld, different from the one predicted by the first gradient model.

1 Introduction

Ductile failure is a major mode of fracture of metals under monotonic loading, at medium to high temperature. It can occur during an accidental condition provoking crack propagations associated with large plastic deformations, eventually leading to the catastrophic failure of industrial components. However the numerical reproduction of crack propagation still requires improvements of the theory of Fracture Mechanics in order to be truly predictive. The developments of this theory is therefore crucial to the improvement of industrial safety regulations.

The elastoplastic constitutive models developed from the fundamental works of Gurson [1] take into account the physical mechanisms responsible for ductile damage: nucleation (usually through debonding of the metallic matrix around inclusions), growth and coalescence of cavities. These local approaches of ductile fracture were significantly improved over the last 10 years by taking into account the effects of work hardening, viscosity, void shape and contact of the voids' boundaries with the enclosed inclusions (works of Gologanu, Siruguet, Flandi).

Additionally, a "micromorphic", second-gradient model applicable to ductile porous materials has been proposed [2]. The goal of this model is to solve the problem of unlimited localization of strain and damage due to softening, inevitable in conventional softening models. As its implementation in a finite element code involves a large number of degrees of freedom, a specific method of numerical resolution has been used to permit the convergence of the model [3][4]. It has been successfully applied to study the failure behaviour of standard fracture specimens such as tensile axisymmetric (TA) pre-cracked

specimens of A508 steel, and Compact Tension (CT) specimens of 316L stainless steel.

This paper presents the application of this new model to the more complex case of crack propagation in a Dissimilar Metal Weld. It organizes as follows:

- Section 2 is dedicated to a brief introduction of the second gradient model for porous metals.
- Section 3 presents the experimental failure test of a Dissimilar Metal Weld.
- Section 4 describes the numerical model representing the experiment.
- Section 5 presents the results of both the first and second gradient model on the case studied
- Section 6 discusses their performances to reproduce the experimental observations. Their relevance is discussed in terms of failure mode and in terms of physical interpretation of the internal parameters of the model.

2 First and Second gradient model for porous metals

The problem of unlimited strain localization is well known in local approaches of failure. It is inherently related to the softening nature of such models, which softens the most loaded regions, which in turn will be more severely loaded and softened. This phenomenon results in the accumulation of very large strains in the smallest elementary volume: one finite element. Ultimately, the prediction of softening is dependent on the mesh size, which is not acceptable.

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This issue is most commonly solved by introducing a heuristic inner-length to the ductile model. An averaging of the local damage or load state is then performed within this inner-length, thus spreading the softening over this length. This can efficiently make the prediction of softening independent of the mesh size, provided that the mesh size is small enough compared to the inner-length.

This is for example the case of Gurson's original model for porous plasticity, modified by Tvergaard and Needleman [6][7]. This model has been extensively used to predict the ductile failure behaviour of fracture specimens and pipes [10][11]. It considers metals as an incompressible matrix in which an initial porosity can grow and coalesce. Its formulation classically involves the first gradient of the nodal field, with the following yield surface:

$$F(\sigma, \sigma_y, f^*) = \frac{\sigma_{eq}^2}{\sigma_y^2} + 2qf^*ch\left(\frac{3}{2}\frac{\sigma_m}{\sigma_y}\right) - 1 - q^2f^{*2}$$

σ_{eq} is the Von Mises equivalent stress and σ_m is the mean stress. Coalescence is approached by $f^* = f$ if $f < f_c$ and $f^* = f_c + \delta \cdot (f - f_c)$ if $f > f_c$, with f_c and δ heuristic parameters representing the void coalescence over a critical porosity f_c [6]. The porosity f evolves from an initial value f_0 with $\dot{f}$ given by the mean plastic strain rate $\dot{\epsilon}_{kk}^p$ and the porosity by the relation $\dot{f} = (1 - f)\dot{\epsilon}_{kk}^p$.

q is a the Tvergaard parameter [7]. The value of $q = 4/e$ is used following the works of Perrin and Leblond [8]. It represents an equivalent porous matrix surrounding the porosity. Matrix hardening is introduced by $\sigma_y(\epsilon_{eq}^p)$, being the stress associated to the plastic strain ϵ_{eq}^p on the uniaxial tensile curve.

In the Gurson model above, independence on the mesh size is given by a heuristic averaging of the porosity rate $\dot{f}$ on a volume given by an inner-length [9]. This model is labelled in this paper as the first gradient Gurson model.

The second approach used on this study to solve the problem of dependence on the mesh size is the one proposed by Gologanu et al [2]. This approach lays on micromorphic basis, as it extends the original homogenization of a hollow sphere of Gurson to take into account the local variation of the strain field at the scale of the porosity. This extended Gurson criterion then writes as follow:

$$F(\sigma, m, \sigma_y, f^*) = \frac{1}{\sigma_y^2} \left(\sigma_{eq}^2 + \frac{Q^2}{b^2} \right) + 2qf^*ch\left(\frac{3}{2}\frac{\sigma_m}{\sigma_y}\right) - 1 - q^2f^{*2}$$

Additionally to the variables defined above, m is a third-rank tensor representing the local moment, and Q^2 is a quadratic form of the components of m . This model has been improved by the works of Enakusta et al [3], and further implemented by Bergheau et al [4]. The originality of the latter implementation is the fact that it does not introduce additional degrees of freedom. The reader is invited to refer to this latter work for further details on the theoretical basis of this model.

The inner-length b is therefore inherently accounted for in this extended yield criterion. Independence on the mesh size has been proven, as well as the ability to successfully reproduce the ductile failure of TA and CT steel samples [4]. This model is referred in this paper as the second gradient Gurson model.

3 Crack propagation in a Dissimilar Metal Weld on a Notched Tensile Test

Dissimilar Metal Welds (DMW) are of major interest in Nuclear Power Plants. They are principally used in the primary circuit as connections between large ferritic components such as the pressure vessel, and the austenitic cooling lines. The fracture toughness of the assembly highly depends on the fracture properties of the DMWs, and these are therefore of high interest. **Figure 1** shows a cross section of such a DMW.

Figure 1 - Dissimilar Metal Weld in French nuclear power plants [5].

The experimental investigation presented below has been carried out in the framework of the doctorate of Fanny Mas [5]. It focuses on the interface between the ferritic steel and the 309L buttering, and more particularly on the failure properties of this interface.

For the sake of simplicity, the case of the internal cladding of ferritic components has been chosen, exhibiting chemical and microstructural gradients across the interface similar to those found on other DMWs joining ferritic and austenitic pipes. The cladding is made of a first layer of 309L and a second layer of 308L, joined by Submerged Arc Welding to the ferritic internal surface.

After the welding process, a Post-Welding Heat Treatment (PWHT) is performed in order to reduce the residual stresses in the DMW. The component is heated up at 610°C at a slow heating rate, hold at this temperature for 8 hours, and cooled down at a slow cooling rate.

Solute diffusion, precipitation or dissolution can occur extensively during this treatment, given the large duration and large volume of material involved. On the opposite, the welding process involves significantly shorter durations for a given volume of material, insufficient for these phenomena to become significant.

3.1 Metallurgical observation of a Dissimilar Weld Metal after PWHT

Micrographic views of the interface between the 18MND5 and the 309L strip before and after PWHT are shown in **Figure 2**.

Figure 2 – (Top) Micrographic views of the interface between the 18MND5 and the 309L after etching. (Left) Before PWHT. (Right) After PWHT. (Bottom) Nano-hardness measurements across the fusion line, before and after the heat-treatment [5].

Observations conducted in the work quoted above concluded in the identification of the following zones before PWHT [5]:

- The base metal 18MND5 with a bainitic microstructure (ferritic lath and Fe_3C carbides).
- A Heat Affected zone in the 18MND5. Its width can stretch over 10 mm.
- A thin martensitic layer is found at the interface. Its width is irregular and varies from 5 to 200 microns.
- A fully austenitic zone is seen next to the martensitic layer on the side of the 309L. Its width is about 70 microns.
- The 309L weld metal exhibiting $(\delta + \gamma)$ microstructure, with residual δ -ferrite embedded in the γ -austenitic matrix.

During heat treatment, dissolution of the carbides in the 18MND5 and diffusion of the carbon from the 18MND5 to the 309L are observed. This results in the following modifications of the microstructure [5]:

Formation of large ferritic grains of 18MND5 (over 200 microns) next to the fusion line. They show a very low carbon contents and no or little carbides. Further in the

18MND5, the nominal content of carbon is found only at 500 microns from the fusion line.

Carbon enrichment of the martensitic layer and of the purely austenitic layer in the weld side. Precipitation in carbides takes place over 70 microns from the interface.

Nano-indentations across the fusion line before and after the heat-treatment has been performed [5], and confirms these observations. Figure 2 shows these measurements, exhibiting a decrease in hardness in the 18MND5, and an increase in the weld metal. This latter increase takes place in a thin zone next to the fusion line, in the carburized martensite and austenite.

3.2 Notched Tensile Test

Decarburization of the 18MND5 such as observed above might impact the overall toughness of the DMW. To address this question, a specific notched tensile test has been designed to assess the failure behaviour of this zone particularly. **Figure 3** shows the geometry of one test sample. The test sample is flat, 0.81 mm thick, normal to the fusion surface. It includes both a 18MND5 zone and a 309L zone, with the fusion line.

A notch reduces the cross section of the specimen right on the decarburized zone. The dimensions of the specimen are detailed in the **Table 1**.

Figure 3 - Geometry of Notched Tensile Test [5].

Table 1 - Dimension of the notched tensile specimen [5].

Thickness	0,81 mm
Width	1,995 mm
Notched width	1,004 mm
Effective length	8,025 mm
Notched cross-section	0,846 mm ²
Size of decarburized zone	0,2 mm
Mean thickness of martensite layer	5 μm

The tensile load is applied at the specimen ends by clamping. The notch opening distance is measured on the optical recordings carried out during the test. The average between the opening distance of the top and the bottom notch is considered. The result of the tensile test is shown in **Figure 6**. Failure occurs in the decarburized zone.

4 Numerical model of the specimen

Appropriate assessment of the failure behaviour of the decarburized zone is proposed through the local approach to fracture. This section presents the numerical set up of the model. The SYSTUS^{TM} software [12] has been used to carry out the simulations, and Visual Mesh^{TM} [13] for the model geometry.

4.1 Specimen geometry and behaviour zones

One fourth of the specimen is modelled by mean of symmetry, including only one half of its thickness and one half of its width. The entire length is modelled because of the dissymmetric nature of a Dissimilar Metal Weld. The model is discretized with linear 8-nodes hexahedral elements, with selective reduced integration. 16550 elements and 20559 nodes are used for one fourth of the specimen. **Figure 4** illustrates the geometry of the numerical model.

Figure 4 - Modelled geometry of the notched specimen.

The gradients of mechanical properties in the specimen has been modelled by various homogeneous zones representing their average expected behaviour. For instance, the progressive decarburization observed on the 18MND5 when increasing the distance to the fusion line is approached by only 2 behaviour zones (labelled 'Decarburized' and 'Medium decarburized'). Identically, the progressive carburization of the austenite when decreasing the distance to the fusion line is approached by only 2 behaviour zones (labelled 'Hard' and 'Soft').

The 18MND5 found in the specimen with the nominal carbon content (over 500μm from the fusion line) is considered homogeneous, as well as the 309L. In total, seven different behaviour zones have been defined, as shown in Figure 4. The

Table 2 lists their dimensions and mesh sizes.

Table 2 - Dimensions and mesh sizes of the various behaviour zones.

Behaviour Zone	Thickness (μm)	Mesh size (μm)
18MND5	on the left end	60
18MND5 Medium decarburized	300	17
18MND5 Decarburized	200	11
Martensite	5	5
Hard austenite	35	9
Soft austenite	35	9
309L	on the right end	60

On the basis of experiments carried out in the works quoted above [5], the monotonic stress-strain curves of each of the behaviour zone have been identified. The Table 3 details their elastoplastic properties.

Table 3 - Elastoplastic properties of the various behaviour zones.

Behaviour Zone	Young Modulus (GPa)	Yield Stress (MPa)	Strain hardening	Ductile failure
18MND5	237	530	Isot.	-
18MND5 Medium decarburized	237	347	Isot.	-
18MND5 Decarburized	230	297.5	Isot.	Yes
Martensite	230	1814	-	-
Hard austenite	234	2275	-	-
Soft austenite	229	1261	-	-
309L	196	349.3	Isot.	-

The strain hardening of the softer materials are shown in Figure 5, and represented by an isotropic model. The harder materials, i.e. the martensite and the carburized austenite, have shown little or no strain hardening, and are modelled with nearly perfect plasticity.

Figure 5 - Strain hardening curves identified for the softer behaviour zones.

4.2 First and second gradient models of ductile damage for the decarburized zone

The study of the ductile failure of the decarburized zone has been carried out with the local approach to failure. The failure model is applied only on the behaviour zone labelled '18MND5 Decarburized'. The two variants of the original Gurson model presented in section 2 are compared: the first gradient and second gradient variants. The first gradient model has been used in this behaviour zone with selective reduced integration. The second gradient model has been used with one modification of the integration scheme.

Selective reduced integration is appropriate with linear elements submitted to incompressible plasticity. It is however irrelevant for porous plasticity. The integration schema has therefore been adapted to dynamically switch on the selective reduced integration only for the elements showing compressive stresses and porosity inferior or equal the initial porosity.

Both models share the same definition of parameters left to the user to reproduce the experiments. The Table 4 presents the values of these parameters. The initial porosity is chosen as a reasonable density of inclusions present in the decarburized layer: 10^{-4} . The inner-length is approximately deduced from the fractured surfaces as an average distance between the voids: 50 μm . The coalescence parameters are left for fitting the experimental load versus notch opening distance.

After fitting the coalescence parameters, very different values of the porosity at coalescence were found between the two variant models. The one found for the first gradient model being extremely close to the initial porosity.

Table 4 - Parameters set for the two variants of the Gurson model to represent the experimental curve.

Gurson variant	f_0	f_c	δ	b (μm)
First gradient	10^{-4}	$10.5 \cdot 10^{-4}$	6.0	50
Second gradient	10^{-4}	$5.0 \cdot 10^{-2}$	2.0	50

5 Results

The comparison of the performances of the two variants of the Gurson model (first gradient and second gradient) are detailed in regards of two experimental outputs. The first one is the predicted load versus notch opening curve, and the second one is the failure mode of the decarburized layer. The comparison of the load versus notch opening is not as interesting as the comparison of the failure mode, as the coalescence parameters have been specially set for a satisfactory representation of the measured curve.

The simulation with the first gradient model has completed 30 time steps in 1 hour and 30 minutes with 6 processors, while the simulation with the second gradient model has completed 28 time steps in about 32 hours with 6 processors.

5.1 Load versus notch opening curve

Satisfactory agreement have been reached between the load versus notch opening curves as measured and as predicted by the two variants of the Gurson model, as shown in Figure 6. The measurement of Notch opening has been slightly offset by a value of $-8\mu\text{m}$ for better agreement with calculations. This is assumed acceptable.

The two variants of the Gurson model can successfully reproduce the measured curve up to instability by adjusting the coalescence parameters. The second gradient model encountered a convergence issue during the final collapse of the notched section, stopping the simulation as shown in Figure 6. The first gradient model did not encountered such issues. Apart from this, no significant differences can be noted in the output of the two models.

Figure 6 - Load versus notch opening curves as measured and as predicted by the two variant of the Gurson model.

5.2 Failure mode of the decarburized layer

The location of failure in the decarburized layer is analysed in this section. The Figure 7 and Figure 8 illustrate the failure location as predicted by the two variants of the Gurson model at similar level of damage. For that purpose, locations where the porosity is greater than 0.03 are displayed in black, while other locations are displayed in white. Figure 7 illustrates the porosity field seen from the outside of the specimen, while Figure 8 illustrates it from the inside, in the bulk material located on the planes of symmetry.

In the case of the first gradient model, the porosity starts to grow in the centre of the notched section, at about 150 μm from the fusion line in the decarburized zone. It then develops to reach the free surfaces and comes closer to the fusion line, at about 40 μm from the fusion line on the external corner. With the second gradient model, the porosity grows first right next to the fusion line, around the external corner. It then develops to cover most of the notched section next to the fusion line, and later tends to distance itself from the fusion line when coming closer to the centre of the notched section. The predictions of failure mode by the two variants of Gurson model are thus almost opposite.

Figure 7 - Comparison of the failure location in the decarburized layer as seen from the outside. Left: First gradient model, notch opening=0,236 mm. Right: Second gradient model, notch opening=0,225 mm.

Figure 8 - Comparison of the failure location in the decarburized layer as seen from the mid specimen symmetry planes. Left: First gradient model, notch opening=0,236 mm. Right: Second gradient model, notch opening=0,225 mm.

The presence of harder behaviour zones can be noticed on the side of the 309L, either with the first gradient or second gradient model. They show minimal deformation compared to the soft decarburized zone, acting as a shield on the side of the 309L.

6 Discussions

This paper have shown the performances of two variants of the Gurson original model of ductile fracture applied to a 3D simulation of the failure of a Dissimilar Metal Weld. Both models are non-local, i.e. solve the problem of unlimited strain localization. The first gradient model solves it on a purely heuristic way, while the second gradient model solves it on a micromorphic basis. Both models are able to reproduce the global measurements of load and notch opening measured experimentally.

The following remarks can be drawn from this study:

- To the knowledge of the authors, this study is the first investigation of the ductile failure of a Dissimilar Metal Weld with a local approach solving the issue of unlimited strain localization on a micromorphic basis.
- The performances of the second gradient model in terms of CPU time and convergence is satisfactory in regards to the level of complexity of this model. It justifies further efforts to improve its performances.
- As previously noted [4], appropriate values of porosity at coalescence required for an experimental match for the second gradient model are very different from those required for the first gradient model.

Indeed, the first gradient model knows only the local mean stress as driving force for void growth. The second gradient model however knows an additional

driving force for void growth, i.e. the local ‘moment tensor’. For a given loading situation, void growth will therefore be stronger with the second gradient model than with the first gradient model.

The value of porosity at coalescence of the second gradient model are much more in accordance with micromechanical data either approached by measurements or by simulations. This observation clearly argues in favour of the second gradient model.

- The development of damage in the decarburized zone such as presented by the works of F. Mas [5] is a clear discriminant between the first gradient model and the second gradient model. They predict an almost opposite failure mode. One can explain this difference by the different driving forces taken into account for void growth.
- Mean stress is first found the centre of the notched section, sufficiently away from the hard zones that shield their immediate surrounding. The first gradient model hence predicts the first void growth in this zone. The ‘moment tensor’ is strong along the fusion line due to the strong gradient of mechanical properties. It therefore strongly modifies the prediction of the failure mode of the second gradient model.
- Clear experimental observations are missing to give a final appreciation of the differences between the two variants of the model. They should state whether the damage starts at the centre of the notched section away from the fusion line, or along the fusion line on the external surface.

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