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ORIGINAL ARTICLE

# The influence of the growth cavity on damage of welded steel

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**Abstract** The aim of our work is the modeling of damage in the welded metal using the finite element method and the concepts of fracture mechanics based on local approaches. The use of Gurson-Tvergaard-Needleman (GTN) model has enabled us to model the behavior of damage of welded steel, which is described as being due to the growth of cavities.

**Keywords** Growth of cavities · Volume deformation · Damage · GTN · Weld · Steel

## 1 Introduction

In the past three decades, simulation of ductile damage behaviors in metallic materials had known a large deformation in the development of several continuous models, the evolution of damage in the stress triaxiality is the key to each these studies. Today, ductile fracture is governed by three physical mechanisms: initially, nucleation of inexistent cavities, after, growth of these cavities in an appropriate loading, and finally, the coalescence of adjacent cavities. The study of this failure mechanism involves the use of local approaches that are based on knowledge of the field of stress and strain.

McClintock's work and those of Rice and Tracey, based on the growth of cavities, is an undeniable contribution to the development of fracture mechanics. These approaches considered that the rate of growth of the cavities is modeled by an exponential function based on the rate triaxiality constraints $\tau$, defined by the ratio $\sigma_m/\sigma_{eq}$. From this work, several models have been proposed, in particular, based on continuous damage models (coupled models) as the model of Gurson.

Gurson has developed a constitutive model for porous ductile media, based on a rigid-plastic material behavior, and the upper bound theorem of plasticity, based on detailed phenomenological studies of the behavior of materials containing periodic distributions of cylindrical and spherical voids.

Our goal is to provide a methodology possibly including finite element modeling to describe the various pathways for study options and choose the most appropriate approach to the description of failure mechanisms of welded steel. We will perform a mechanical characterization to identify the major physical phenomena to be considered in modeling. On this basis, we propose the approach of a constitutive and a damage criterion specific to welded steel.

## 2 Presentation of the Gurson-Tvergaard-Needleman (GTN) model

The experimental results indicate the central role of the growth of cavities in ductile metals [1–3]. All these studies have focused on metallic materials and showed that the cavities formed on the second phase particles, or by decohesion between a particle and the matrix, or the rupture of a particle. The final rupture occurs after the growth phase of adjacent cavities until their final coalescence. Analysis growth of cavities in infinite plastic material shows that this growth is highly dependent on the hydrostatic stress [4, 5]. And the coalescence of the cavities is generated by a high rate of triaxiality. This prediction was confirmed by a series of specimens tested on more severely notched least in the case of steel [6, 7].

Given the experimental results, there has been a growing interest in the use of the growth and coalescence of cavities to

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describe ductile metals. Many examples of research focused on the growth of a single cavity in an infinite elasto-plastic solid, for different stress states [4, 5, 8]. Based on analyzes equivalent to a spherical cavity, Gurson developed a model to describe the behavior of a ductile porous solid [9, 10]. In this model, the parameter $f$, volume fraction of porosity, is the only parameter of material damage and the response is very sensitive to its evolution. This model was extended by Needleman and Rice to account for the germination of cavities [11], and then by Tvergaard and Needleman to reflect the coalescence of cavities [12, 13]. Gurson-Tvergaard-Needleman (GTN) model is based on the micromechanical model developed by Gurson [9]. It allows describing the growth of a spherical cavity in a rigid perfectly plastic matrix leading to the expression of the plasticity criterion given by (1):

$$\Phi = \frac{{\sigma_{eq}}^2}{{\sigma_y}^2} + 2f^*.q_1.\cosh\left(\frac{3}{2}q_2\frac{\sigma_m}{\sigma_y}\right) - \left(1 + q_3\left(f^*\right)^2\right) = 0 \qquad (1)$$

With the constitutive parameters $q_1$, $q_2$, $q_3$ ($q_3=(q_1)^2$).

$f*$ represents the modified volumetric void fraction which is the function of $f$ defined by:

$$f^* = \begin{cases} f & \text{for } f \le f_c \\ f_c + \delta(f - f_c) & \text{for } f > f_c \end{cases}$$

with

$$\delta = \frac{f_u^* - f_c}{f_F - f_c} \qquad (2)$$

Where $f_u^*$ is the ultimate value of $f^*=1/q_1$, $f_F$ the volume fraction of void in the final rupture and $f_c$ the critical volume fraction of void.

The volume fraction of void $f$ is divided into a new term nucleation cavities $f_{nucleation}$ and a second term $f_{growth}$ corresponding to the growth of existing cavities. The change of the volume fraction of cavities is given by the following expression:

$$df = df_{nucleation} + df_{growth}$$

with

$$df_{growth} = (1 - f)d\varepsilon_{kk}^p \qquad (3)$$

and

$$df_{nucleation} = ad\varepsilon_{eq}^p \qquad (4)$$

where $\varepsilon_{kk}^p$ the total of normal component of the plastic deformation, $\varepsilon_{eq}^p$ the equivalent plastic strain. The parameter of germination «a», which is selected in the event that the void nucleation follows a normal distribution, depends on the equivalent plastic strain.

To calculate a cracked structure using the GTN model, several parameters are required:

– Generally, the constitutive parameters are fixed at $q_1$=1.5, $q_2$=1 et $q_3=(q_1)^2$. In a recent study, Perrin and Leblond [14] have demonstrated the existence of a correlation between the parameter $q_1$ and porosity $f$ and for a porosity tends to zero $q_1$ takes the value about 1.47. Under a wide bibliographic study on the model parameters of GTN, it was shown that the parameter $q_1$ takes values between 1.1 and 1.5 [15].
– $f_0$, initial porosity, is a parameter related to the material (measured from microscopic observations or estimated from the formula of Franklin).
– δ which represents the slope acceleration of the growth of porosity and «a» parameter of the continuous germination may be arbitrarily set or adjustable parameters considered.
– $f_c$, which corresponds to the onset of coalescence, is an adjustable parameter using numerical simulation.

## 3 Law of behavior

To determine the behavior law of welded steel, we used an experimental test geometry corresponds to ASTM D638 M1A, Fig. 1. The test was made on Instron tensile machine, the mechanical properties of welded steel for a speed of 0.001 $s^{-1}$ and at room temperature 23 °C are given as follows:

BM (base metal):

E = 183 GPa and $\sigma_e$ = 300 MPa and υ = 0.3.

WM (weld metal):

E = 180 GPa and $\sigma_e$ = 400 MPa and υ = 0.3.

HAZ (heat affected zone):

E = 450 GPa and $\sigma_e$ = 205 MPa and υ = 0.3.

Working on axisymmetric notched specimens (AE), it is possible to study the multiaxial stresses, only using a tensile test. These samples are used to study conditions of plane strain and plane stress.

For a notched specimen, as the elastic limit is not exceeded, the maximum stress is in the bottom of the notch by the phenomenon of stress concentration. The elastic limit is reached first at this point. If the test continues to be deformed plastically, deformed zone extends and eventually invade the entire notched section. The load then reaches the limit load of the specimen; it is greater than it would be without fault (notched). Consider for that first a cylinder of material in the notch portion of the specimen, if it were isolated, lengthen it along its