STUDY OF FRACTURE CRITERIA FOR DUCTILE RUPTURE OF A508 STEEL

F.M. Beremin[1]

Centre des Matériaux de
L'Ecole Nationale Supérieure des Mines de Paris
B.P. 87 - 91003 Evry Cédex, France

ABSTRACT

This investigation deals with the determination of damage functions which can be employed for modelling ductile rupture of A508 steel. These functions are derived from experiments conducted on specimens calculated by a finite element method. The formation of cavities from MnS inclusions obeys a critical stress criterion whilst cavity growth rate can be reasonably described in terms of the Rice and Tracey expression. The cavity growth rate at rupture decreases as the stress triaxiality is increased. A finite element calculation shows that crack initiation in axisymmetric precracked specimens is consistent with the attainment of a critical cavity growth rate in the first element located at the crack tip.

KEYWORDS

Rupture; cavity nucleation; cavity growth; cavity coalescence; numerical calculations.

INTRODUCTION

The ductile tearing of low and medium strength materials has been given considerable attention because of its practical importance. In particular many studies have been devoted to non linear fracture mechanics approach, see e.g. Rice (1968) and to its applicability in computer programs (e.g. EPRI report, 1978). This approach attempts to define the asymptotic form of the stress and strain fields for a stationnary crack (Hutchinson, 1968; Rice and Rosengren, 1968) or for a moving crack (Amazigo and Hutchinson, 1977; Rice and Sorensen, 1978). A single parameter (e.g. J or C.O.D.), depending of the geometry and loading conditions of the problem

---

[1] F.M. Beremin is a research group including Y. d'Escatha*, J.C. Devaux**, P. Ledermann*, F. Mudry*** and A. Pineau***, from :
* Bureau de contrôle de la construction nucléaire, 3, rue de Vosges, 21000 Dijon.
** Division des Fabrications de Framatome, B.P. 13, 71380 Saint-Marcel.
*** Centre des Matériaux de l'Ecole des Mines de Paris, B.P. 87, 91003 Evry Cédex, ERA n° 767.
F. Hourlier*** and J.C. Lautridou*** were also involved in this study.

characterizes the strain stress field at the crack tip. Rupture or stable crack growth is obtained when this parameter reaches a critical value e.g. J_{1c} (Begley and Landes, 1972), C.O.D.$_c$ (e.g. Knott and Green, 1976) or $(dJ/da)_T$ (Paris and coworkers, 1977). This approach is difficult to use when non symmetric geometries or complex and non isothermal loadings are present.

Another possible approach is the systematic use of a finite element method in order to compute as precisely as possible the stresses and strains in any point of a structure. A damage function is then calculated in each element to describe the rupture process. The node release technique is employed to simulate crack initiation and crack propagation when a critical value of the damage function is reached. This second approach has been used by several authors (EPRI report 1978, Rousselier, 1979). In particular, d'Escatha and Devaux (1979) have shown that a simple damage function simulating the growth of holes around inclusions can give very reasonable results. The aim of this study is the experimental determination of this function for a A508 steel.

This damage function must describe the physical events taking place during the ductile rupture process. It is well known that ductile rupture involves three main stages. First cavities are nucleated from inclusions. Then these cavities grow under the combined effect of plastic deformation and stress triaxiality. Finally, in our material a catastrophic coalescence phenomenon takes place by the formation of shearing bands which link together the holes. This paper is divided into 3 parts which correspond to each stage of the ductile rupture process. Cavity coalescence is analysed in some details in the case of bulk material, i.e. in the case corresponding to relatively small stress and strain gradients found in notched specimens. The situation corresponding to a crack tip is also considered.

MATERIAL

All the experiments were performed at 100°C on a A508 class 3 steel taken from a nozzle shell of a P.W.R. nuclear vessel. Its chemical composition and its tensile properties at 100°C are given in Table 1. In this material most inclusions are MnS type I particles of almost ellipsoïdal shape. Tests were carried out both in the longitudinal and in the short transverse direction.

TABLE 1

Chemical composition								Tensile properties at 100°C		
C	S	P	Si	Mn	Ni	Cr	Mo	$R_{0,2\%}$ (MPa)	R_T (MPa)	Σ (%) (Long)
0,144	0,009	0,011	0,185	1,225	0,70	0,26	0,510	421	553	72

RESULTS AND DISCUSSION

Cavity Formation

The observation of cavity nucleation has been made on polished sections of deformed circumferentially notched specimens. The geometry of these specimens is shown in Fig. 1. In these specimens the stress triaxiality in the center can be changed by varying the notch radius. Moreover these geometries were chosen because they permit to obtain relatively small stress and strain gradients. These two properties facilitate the interpretation of metallographic observations. Finally straightforward 2 dimensional finite element simulation can be employed in order to compute the stress and strain distribution in these specimens. The results of these calculations have been published elsewhere (Beremin, 1980a). A map of the damaged inclusions observed on the polished sections has been drawn in each case. A comparison with the stress and strain distribution has been made. The details are given elsewhere (Beremin, 1980b). Here it is enough to say that the following criterion for cavity nucleation was proposed :

$$\Sigma_1 + k\,(\sigma_{eq} - \sigma_o) = \sigma_d, \qquad (1)$$

where Σ_1 is the maximum principal stress, σ_{eq} is the Von-Misès equivalent stress, σ_o is the yield stress, k is a function of inclusion shape and σ_d can be considered as a critical, temperature independent, local stress inside the inclusion. This expression is very close to that already proposed by Argon and coworkers (1975) on different materials. The results of our investigation have shown that the critical strain for cavity nucleation is a function of stress triaxiality. Near a crack tip where the stress triaxiality is very high, cavity formation takes place very easily in our steel. Therefore at a crack tip this first stage in ductile rupture can be neglected.

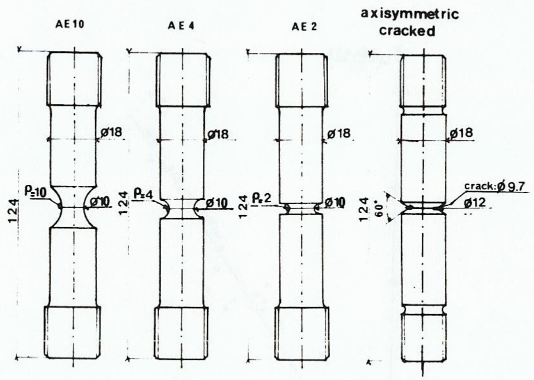

Fig. 1. Geometry of the specimens used.

Cavity growth

Experiments have been performed on circumferentially notched specimens in order to evaluate the cavity growth rate. The specimens were given a well defined amount of deformation at 100°C. Then a sharp notch was machined along the minimum section. Finally the specimens were broken at -196°C with negligible plastic deformation. Scanning electron microscope observations of the fracture surfaces showed the inclusions in their associated cavities surrounded by cleavage fracture. The mean radius of the inclusions and that of the cavities were determined on photographs (Beremin, 1980c).

The results obtained in the short transverse direction are given in Fig. 2 where the cavity growth is compared to the theoretical analysis by Rice and Tracey (1969). In their model which deals with spherical cavities in a perfectly plastic material, these authors have shown that the cavity growth rate can be written as :

$$dR/R = 0.28\, d\varepsilon_{eq}\, \exp(1.5\, \sigma_m/\sigma_{eq}), \qquad (2)$$

This equation was integrated using the values of ε_{eq} and σ_m given by the finite element calculations. It is worth noting that ε_{eq} was obtained by substracting the strain for cavity nucleation. Moreover in equation (2) we used σ_{eq} instead of σ_o in order to take into account the low strain hardening rate of our material. It was noticed that for a given notch radius the stress triaxiality was almost constant during strain history. This allows a straightforward integration of equation (2), i.e. :

$$\mathrm{Ln}(R/Ro) \,/\, \varepsilon_{eq} = \exp\{1.5\, \sigma_m/\,\sigma_{eq} + \mathrm{Ln}\ 0.28\}, \qquad (3)$$

where R_o is the initial size of the cavities taken as the size of the associated inclusions.

Figure 2 shows that equation (3) gives a good description of the cavity growth in the various geometries investigated, except that the pre-exponential constant is close to 0.50 instead of 0.28. This change is a minor difference which has no significant effect on the general trends of the coalescence phenomenon. Hence, in the following, all the cavity growth rates are calculated by integration of equation (2).

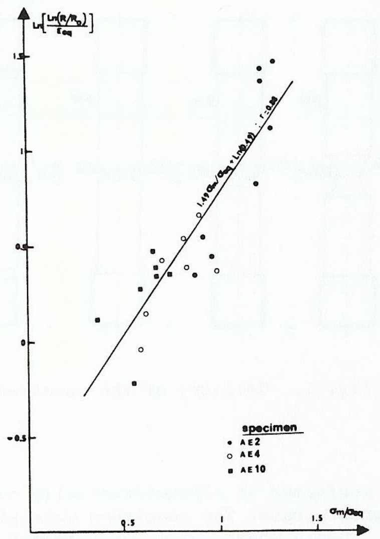

Fig. 2. Measured cavity growth rate.

Cavity coalescence

Bulk material behavior. Metallographic observations of specimens unloaded just before rupture show cavities linked by a narrow band where intense shearing seems to take place (Beremin, 1980c). The distance between the cavities is still large as compared to their radius. Thus in our material the holes do not grow until they touch each other as assumed in some models (McClintock, 1968).

A calculation of the critical cavity growth rate $(R/R_o)_c$ at rupture has been made on the notched specimens. For those geometries, it was shown previously that the initiation of final rupture in the center of the minimum section could be easily defined (Beremin, 1980a). Since the strain for cavity nucleation and the rupture strain are known in the center of the specimens, $(R/R_o)_c$ can be computed. However this requires some extrapolation of the finite element results for average strains larger than those computed, as already discussed (Beremin, 1980a). The results of these calculations are shown in Fig. 3 where the vertical lines include the experimental scatter as well as the systematic error which can arise from the extrapolation technique. The triaxiality plotted on the horizontal axis corresponds to an average value over the strain history. Except in the case of the tensile test, σ_m/σ_{eq} is almost constant, as stated previously. The results corresponding to the longitudinal and the short transverse direction are given.

These results show a weak variation of $(R/R_o)_c$ as a function of stress triaxiality. Different critical growth rates are observed between the two directions. This difference can be easily explained by the different initial radius of a cavity nucleated on an inclusion in each case. In the longitudinal direction the mean inclusion radius is 4µm, whilst in the transverse direction it is 7 µm. More surprising is the significant decrease in the critical growth rate when the stress triaxiality is increased. The reasons for this behavior are not yet clear. It is felt that statistical considerations should have led to a reverse trend (Beremin, 1980c).

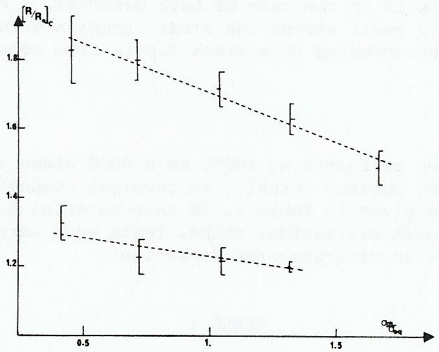

Fig. 3. Critical cavity growth rate evaluated from the rupture of circumferentially notched tensile specimens.

Crack tip situation. A certain number of difficulties arise if it is attempted to use the results of the above section for modelling ductile rupture at a crack tip. First the stress triaxiality is more important and an extrapolation of the experimental results must be attempted. Second, the coalescence phenomenom does not take place between two cavities but between a cavity and the blunted crack. Finally the stress and strain gradients are very steep. This last aspect is likely the main difficulty. To deal with this problem, many authors introduce a process zone over which average values for the stresses and strains are used (e.g. McClintock, 1968). In a finite element program the stresses and strains computed in each element are already average values. Therefore the first element near the crack tip can be considered as a process zone. Its size should be a material constant. D'Escatha and Devaux (1979) have already shown that a constant mesh size gives all the physical trends of the scale effect either for crack initiation or for crack propagation.

The size of the process zone must be associated with metallurgical dimensions such as the distance between inclusions or the C.O.D. at crack initiation (e.g. Rice and Johnson, 1970; Beremin, 1980c).

In our material experiments have already been conducted on CT50 specimens (Lautridou, 1980). It was shown that the C.O.D. at crack initiation $(C.O.D.)_c$ was about 200 µm. Therefore this value was chosen for the size of the first mesh element. Moreover, in the present study we used axisymmetric cracked tensile specimens (Fig. 1) in order to avoid assumptions about plane strain or plane stress state usually made for plate specimens. Two different modelisations for these specimens have been performed (Beremin, this issue). The first one uses element sizes of 200 µm near the crack tip. This type of mesh was used in the present study. Eight nodes isoparametric elements were employed with small strain incremental plasticity, Von-Misès criterion and geometry actualization. The experimental stress-strain curve determined at 100°C was employed. It was shown previously that centered fatigue cracks could be obtained in these geometries (Hourlier and Pineau, 1979).

The experiments were conducted at 100°C in the longitudinal direction. The displacement δ was measured between 2 symmetrical points located 23.5 mm on both sides of the crack. Interrupted tests were used to measure the mean crack advance Δa. It was observed that stable crack growth occurred and that the crack remained axisymmetric during propagation. Catastrophic failure occurred for δ = 1.3 mm. The examination of the fracture surfaces showed ductile rupture, whilst the macroscopic aspect of the two parts of the specimens is schematically described in Fig. 4. All the experimental results are summarized in this figure where the scatter observed on the P-δ curve is included. The interrupted tests allowed the evaluation of the C.O.D. at crack initiation, i.e. $(C.O.D.)_c$ = 210 µm.

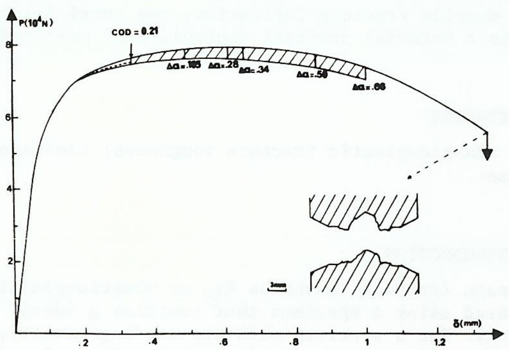

Fig. 4. Experimental results on axisymmetrically cracked specimens.

The comparison between the calculated and the measured load-displacement curves is made in Fig. 5. In this figure, the plastic zones corresponding to various loading conditions are equally shown. It is worth noting that the whole section of the specimen is plastically deformed when initiation takes place. It is equally noticed that the stress triaxiality near the crack tip σ_m/σ_{eq} = 1.80 is lower than that corresponding to the situation of small scale yielding. The cavity growth rate was calculated in the first element by numerical integration of equation (2). This equation was integrated up to the displacement corresponding to crack initiation (δ_c = 330 µm). This integration leads to $(R/R_o)_c$ = 1.48. This value associated with a stress triaxiality of 1.80 is reasonable as compared to the results obtained

in notched specimens (Fig. 3).

In spite of the fact that these results are based on a limited number of specimen geometries, they strongly suggest the possibility of evaluating the crack tip behavior by using experimental results obtained with notched specimens. This conclusion has some practical interest since, as a general rule, the instrumentation of bulk specimens is much easier than that of cracked specimens. A program using larger specimens in conjunction with the same computational approach is under development. This program attempts to investigate the scale effect and to define more accurately the size of the process zone.

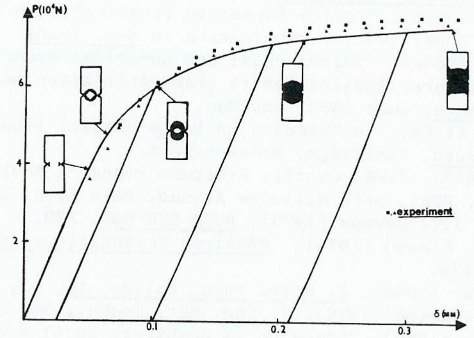

Fig. 5. Comparison between the calculated and the measured load displacement curves on axisymmetrically cracked specimens. The shapes of the plastic zones corresponding to various loadings are shown.

CONCLUSIONS

1. An analysis of the ductile rupture of circumferentially notched tensile specimens has been made. The systematic use of finite element calculations and of metallographic observations allows the determination of a critical stress for cavity nucleation.

2. It is found that in the short transverse direction the cavity growth rate is proportionnal to exp $(1.5\sigma_m/\sigma_{eq})$ which is in agreement with the theoretical model by Rice and Tracey.

3. The cavity growth rate at rupture decreases slowly as the stress triaxiality is increased.

4. It is possible to describe crack initiation in a pre-cracked specimen in terms of a critical growth rate over a characteristic distance at the crack tip.

ACKNOWLEDGMENTS

This work has been partly supported by the D.G.R.S.T. (Contracts N° 78-7-2691 and N° 78-7-2692). Financial support by Framatome for the numerical computations is also greatly acknowledged.

REFERENCES

Amazigo, J.C., J.W. Hutchinson (1977). J. Mech. Phys. Solids, 25, 81.
Argon, A.S.,Im.J. S. Safoglu (1975). Met. Trans. 6A, 825.
Argon, A.S.,Im.J.(1975). Met. Trans. 6A, 839.
Begley, J.A., J.D. Landes (1972). ASTM STP 514, 1.
Beremin, F.M. (this issue). "Numerical modelling of warmprestress effect using a damage function for cleavage fracture".
Beremin, F.M. (1980a). "Calculs elasto-plastiques par le méthode des éléments finis d'éprouvettes axisymetriques entaillées circulairement". To appear in the Journal de mécanique appliquée.
Beremin, F.M. (1980b). "Cavity formation from inclusion in ductile fracture of A508 steel". Submitted for publication in Met. Trans.
Beremin, F.M. (1980c). "Experimental and numerical study of the different stages in ductile rupture. Application to crack initiation and stable crack growth". IUTAM Conference, June 1980, Dourdan.
Bridgman, P.W. (1964) in "Studies in large plastic flow and fracture". Harward University Press, Cambridge, Massachusett.
EPRI Report (1978). "EPRI Ductile Fracture research Review Document". Report n° NP-701-SR, EPRI, 3412 Hillview Avenue, Palo Alto, California.
d'Escatha, Y., J.C. Devaux (1979). ASTM STP 668, 229.
Hourlier, F., A. Pineau (1976). Mémoires Scientifiques de la revue de métallurgie, March 1979, 175.
Hutchinson, J.W. (1968), J. Mech. Phys. Solids, 16, 13.
Knott, J.F., G. Green (1976). J. Eng. Mat. Techn., 98, 37.
Lautridou, J.C. (1980). "Etude de la déchirure ductile d'aciers à faible résistance, Influence de la teneur inclusionnaire". Thèse de docteur Ingénieur à l'Ecole des Mines de Paris, 60, boulevard Saint-Michel, 75006 Paris.
McClintock, F.A. (1968) in "Fracture : an advanced treatise"(ed. H. Liebowitz). Academic Press, N.Y., 47.
Paris, P.C., H. Tada, A. Zahoor and H. Ernst (1977). "A treatment of Tearing Instability" U.S. Nuclear Regulatory Commission Report NUREG-0311 August 1977.
Rice, J.R. (1968) in "Fracture an advanced treatise", (ed. H. Liebowitz). Academic press, 2, 191.
Rice, J.R., M.A. Johnson (1970). In "Inelastic behaviour of solids" (Eds. M.F. Kanninen and coworkers), McGraw-hill, New-York, 641.
Rice, J.R., G.F. Rosengren (1968). J. Mech. Phys. Solids, 16, 1.
Rice, J.R., E.P. Sorensen (1978). J. Mech. Phys. Solids, 26, 163.
Rice, J.R., D.M. Tracey (1969). J. Mech. Phys. Solids, 17, 201.
Rousselier, G. (1979). "Contribution à l'étude de la rupture des métaux dans le domaine de l'élasto plasticité". Thèse d'Etat, Ecole Polytechnique, 91120 Palaiseau.