Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999 F01/5

Development of New Design Rules for Low Ductility Austenitic Steels

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ABSTRACT

In the nuclear industry some components are subjected to irradiation. For austenitic steel the irradiation reduces the ductility of the material. The usual construction codes do not take into account the irradiation effects and can not be applied. Specific design rules paying considerations to material characteristics and also to actual applied load are to be developed to better predict the duration life of such components. This paper presents the results of a comprehensive study aiming at validating such a rule for the prevention of plastic instability and rupture under displacement controlled stress for a particular structure containing a geometrical discontinuity The results concern the experimental investigation on tensile tests with notched and smooth specimens made of high strain - hardened materials, numerical simulations and simplified methods using the concept of elastic follow up factor. It is shown that for materials with low ductility the reduction of the resisting strength of the structure can be evaluated with proposed specific rules that need as input data: the elastic calculation, a value of elastic follow up factor and material characteristics available from the standard tensile test. The values of the elastic follow up for the tested structures are given.

1.INTRODUCTION

1.1. General Background.

In the nuclear industry, some components are subjected to irradiation effects and it is necessary to have predictive method able to evaluate how they can reduce the performance and especially the duration of operation. The usual construction codes like RCC.M [1], ASME Section III [2], or RCC. MR [3] do not give specific rules to take into account irradiation effects. This means that if some irradiation is present these rules are not applicable. However, it is worth mentioning the ISDC rules, [4] proposed to design the ITER fusion reactor. These rules are still under development and validation. It is of practical interest to evaluate how they can be applied.

1.2.Description of the Problem.

The study, presented here, aims at developing new structural integrity criteria to prevent rupture of internal components like screws when they are subjected to displacement

controlled loading in the same time as irradiation. As proposed in the ISDC rules the objective is to derive these rules from conventional elastic analysis and consideration of limit values defined from parameters obtained by classical tensile tests.
The failure mode, here considered does not take into account effect of crack in the fracture mechanics sense. It, deals with plastic instability and rupture as defined for example by the Arrêté de Février 1974 [5] in France.

2.EXPERIMENTAL INVESTIGATIONS

2.1.Material.

The studying material is a 316L stainless steel annealed (1130°C during 6mm followed by an air quenching). The composition of this 316L stainless steel used is the reported in Table 1.

Table 1 : Composition of 316L stainless steel used

Element	C	Si	Mn	P	S	N	Cr	Ni	Mo
Weight (%)	0.025	0.420	1.8	0.026	0.021	0.058	16.85	11.05	2.08

2.2.Effect of irradiation on tensile curves

For stainless steel, it is well known that the effect of irradiation on mechanical properties [6, 7] is an hardening (increase of yield strength and ultimate strength) and a reduction of ductility (uniform and rupture elongation). Billone [8] has presented a detailed characterisation of these behaviours which are illustrated in the Figure 1, where different conventional tensile curves are given for different irradiation doses expressed in dpa. The tests were performed on a 316L (N) steel irradiated and tested at 250°C. It is worth noting that the increment in irradiation doses has many effects on these tensile curves. One is positive : the maximal stress is increased. Two are negative : the maximal deformation and the strain hardening capabilities are reduced. These two last effects are an illustration of the loss of ductility of the material. They clearly indicate that the consequence of irradiation on the mechanical behaviour must be evaluated. From a design point of view, the question is how they can influence the mechanical behaviours and failure phenomena modes of the structural components.

2.3.Validation of a «Model Material»

It is difficult and expensive to perform a large parametric experimental study with structural specimens like screw made of irradiated material. It has been here proposed to evaluate if it is possible to simulate these effects with a strain hardened material at a different temperature. The question is : Can we obtain a strain hardened material which have the same tensile curves than an irradiated material. Four hammering levels have been carried out 15, 25, 35, 45% to obtain four different hardening level. The corresponding tensile curves are presented in the Figure 1 for direct graphical comparison with the tensile curves obtained on irradiated material by Billone [8]. The increment of irradiation has a similar effect as hammering on the increment of maximal stress and on the reduction of the maximal elongation and strain hardening capabilities.
For high hammered levels, we can notice that uniform elongation remains rather important (about 5%) whereas for irradiated 316L at 11.8 dpa, the uniform elongation is almost equal to 0%. The reduction of the area at rupture remains large (over 50%) in both cases. This means that the materials remain ductile but the necking onset appears earlier because

of the very low strain hardening capability of the materials. The similarities in the two categories of tensile curves suggest that the plasticity behaviour involved in the plastic deformation, necking, instability and final rupture are also similar. This validates the use of an hammered material to study plasticity instability of an equivalent irradiated material. Of course, this similitude in the macroscopic mechanical behaviour does not mean that the microscopic phenomenon responsible of the enhancement of stress, for example, is the same for irradiated and hammered 316L. For hammered 316L, the enhancement of stress is due to the multiplication and imbrication of the dislocations whereas for irradiated 316L there is also a lot of lattice point defects, dislocation loops.

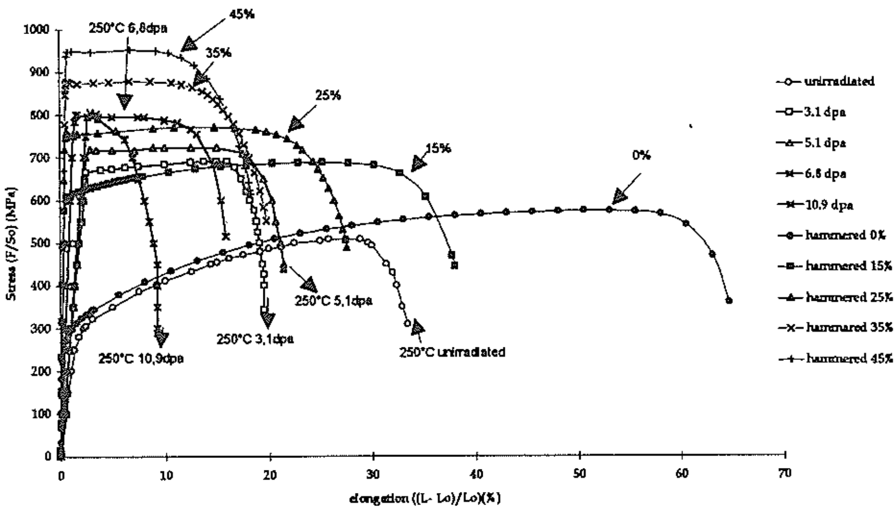

Figure 1 : Comparison of tensile curves of irradiated [8] and hammered 316L

2.4. Structural Effect on Notched Specimens

To study the influence of reduction of ductility on a structural component like a screw, tensile tests on notched specimen made of hammered material were carried out. Tensile tests on notched specimens have been carried out. Three different geometries with different notch radius of 10, 4 and 2mm have been used. The geometry of the AE4 (R=4mm) is given on Figure 2. The main interest of this geometry which is widely used for the development of damage evolution method is that, it is possible to change the concentration effect or stress and strain gradient, constraint effect by changing the initial notch radius R. This geometry can be used to check simply a candidate material to machine a screw that has a sufficient ductility. This is achieved if, at maximal tensile loading, the stress calculated with the initial section is larger than the ultimate stress in the tensile test which is performed on a smooth specimen. During the test performed with AE specimen, the different parameters are recorded: load and diameter of the smallest section. For these specimens the definition of the mean (membrane) strain ε in the smallest section is defined by Eq(1). The results of the test on AE are shown on Figure 3 for the plastic instability and on Figure 4 for the rupture of the specimen. In the both damage, we can notice that deformation are reduced strongly by hardening.

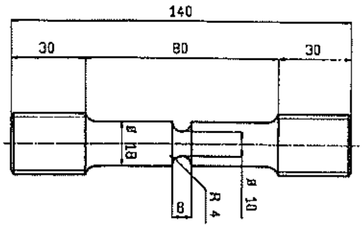

Figure 2 : Notched tensile specimen (AE4) geometry

$$\varepsilon = 2\mathrm{Ln}\left(\frac{D_0}{D}\right) \qquad \text{Eq.(1)}$$

D_0 : initial diameter
D : updated diameter.

3.MODELS TO EVALUATE INSTABILITY AND RUPTURE CONDITIONS OF THE MATERIAL IN THE NOTCHED SPECIMENS.

3.1.Instability Conditions

Different investigators like Bridgman [9] have shown that instability conditions can be correlated with triaxiality factor. This factor is here defined as the hydrostatic pressure divided by the equivalent (Von Mises) stress. This value is calculated at the centre of the reduced section where it is maximal. For AE specimen, it has been demonstrated that the initial triaxiality factor TF is given by Eq(2).

$$\mathrm{TF} = 1 + 3\mathrm{Ln}\left(1 + \frac{a}{2R}\right) \qquad \text{Eq.(2)}$$

a : radius of the minimal section
R : radius of the notch.

TF value is normalised to give the unity in the pure uniaxial stress state. In Figure 3 the values of the mean strains at instability are the points given as a function of TF values calculated for the 3 AE and uniaxial configurations. For AE configurations, the different hammering rates are indicated with different points in the figure. The difficulty to define the mean deformation at instability (because in this region the curves are rather flat) are represented by vertical error segments.

The experimental points indicate that the mean strain at instability first increase with TF values ranging from 1 to 1.5 and then continuously decreases when TF is larger than 1.5. For the different hammered materials, the rational tensile curves were fitted according an Hollomon's relation: $\sigma = k\varepsilon^n$ just before the instability region. The different values of n obtained are n = 0.47, 0.27, 0.14 and 0.085. According to this equation and using the formulae developed by Bridgman and assuming that the R radius does not change during the loading, the following equation was obtained to calculate the strain at instability :

$$\varepsilon^{ins} = \frac{2\left(1+\frac{2}{\alpha}\right)\mathrm{Ln}\left(1+\frac{\alpha}{2}\right)}{2\mathrm{Ln}\left(1+\frac{\alpha}{2}\right)\left(1+\frac{1}{\alpha}\right)+1}\, n \quad \text{with} \quad \alpha = \left(\frac{a}{R}\right)_{initial} \qquad \text{Eq.(3)}$$

$$\varepsilon = n \qquad \text{Eq.(4)}$$

If α tends toward zero, Eq(3) is reduced to the well known Considère's [10] equation (Eq(4)). The values calculated with Eq.(3) are represented by the lines drawn on Figure 3. The experimental points follows the same general trends of reduction against TF and hammering rates as predicted by this equation.

3.2. Rupture Conditions

In Figure 4, the results of the tests on notched tensile specimens are represented by mean strain at rupture plotted versus triaxiality factor. The triaxiality factor is calculated by the Bridgman [9] formula with initial values of the geometry. The results of mean strains at rupture are normalised to the mean strain obtained at rupture for the tensile test on smooth specimen. For ductile materials, Mc Clintock [13] has developed a damage approach (based on void growth) which shown that strain at rupture can be estimated by Eq(5). By normalisation with the strain at rupture available in the tensile test $\varepsilon_{rup}^{tensile}$ and for positive triaxiality factor Eq(5) may be approximated by Eq(6).

$$\varepsilon_{rup} = \frac{B}{\sinh(A\,TF)} \qquad \text{Eq.(5)} \qquad\qquad \varepsilon_{rup} = \varepsilon_{rup}^{tensile} \exp[A(1-TF)] \qquad \text{Eq.(6)}$$

This model gives a fairly good approximation of the experimental results obtained.

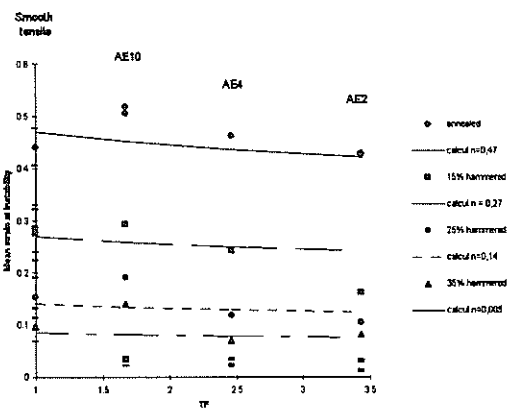

Figure 3 : Evolution of the instability deformation for AE specimens

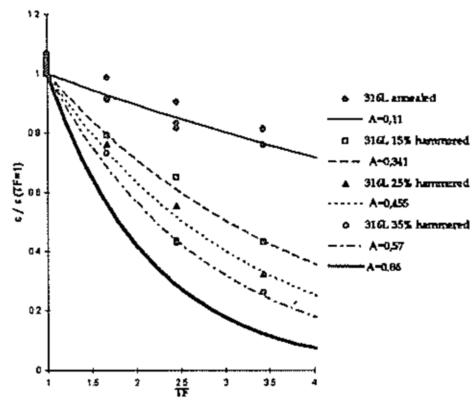

Figure 4 : Normalised mean strain at rupture versus triaxiality ratio

4. DESIGN RULES DEVELOPMENT

It is proposed here to examine the design rules proposed in the IDSC document [4] to take into account the effect of irradiation on the ductility of the material by limiting displacement controlled stresses.

4.1. Description of the Examined Rules

These rules were derived from the work performed by Roche [12] and coming from rules used in the construction codes like RCC.M [1], RCC.MR [3] or ASME Section III [2]. These rules rely on the estimation of the elastic stresses in the structure and for the loading. This stress is called σ_e and is used then to determine the real stress, here called σ. An elastic follow up factor r and the tensile curve of the material are also used. This elastic follow up factor is a simple parameter that indicates how the plastic behaviour, for a category of mechanical structures, is more damaging than the elastic behaviour. This stress σ corresponds to the strain called ε on the tensile curve. The couple (ε, σ) is found on the tensile curve by solving Eq.(11), where the input data are E (Young' s modulus), σ_e, r elastic follow up factor and the tensile curve.

This procedure is presented graphically in the Figure 5 by the step by step procedure described below :

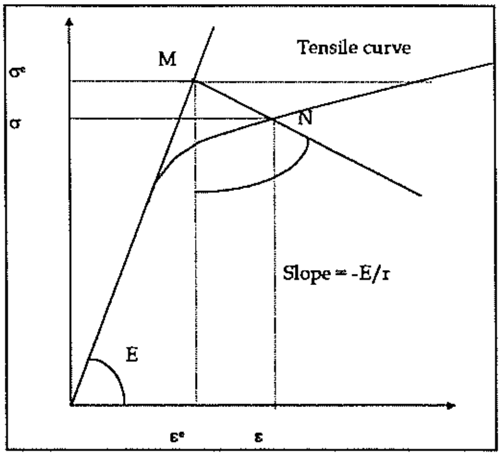

Figure 5 Graphical definition of real stress with elastic follow up factor

$$r = \frac{E\varepsilon - \sigma_e}{\sigma_e - \sigma} \qquad \text{Eq.(11)}$$

1. Calculate σ_e
2. Locate the point M of co-ordinates ($\sigma_e/E, \sigma_e$)
3. Draw the straight line of slope -E/r intercepting the point M.
4. Define the point N, as the intersection of the tensile curve with this straight line.
5. (σ, ε) are the ordinate and abscissa of the point N.

By knowing the real couple (σ,ε), it can be compared to the limited values that are defined in the next paragraph.

4.2. Definition of the Limit values for the Material.

In the case of the notch specimen, the stress under consideration is the mean membrane stress in the smallest section. The stress and strain values presented in the Table 2 can be proposed to prevent the occurrence of instability and rupture as demonstrated in the paragraph 2.

Table 2 : Strain and stress values proposed to prevent the occurrence of instability and rupture

Failure Modes	Limit Values	
	Strain	Stress
Plastic Instability	A_u	S_u
Rupture	ε^{TF}_{rup}	S_{rup}

From a practical point of view, these three limits are obtained directly by the tensile test on smooth specimen, the fourth (ε^{TF}_{rup}) is calculated from the tensile test ($\varepsilon^{Tensile}_{rup}$) with a reduction coefficient (exp(A.(TF-1)) that requires before the determination of A and TF parameters. Furthermore, for material with very low ductility and low strain hardening capacity, a conservative estimation can be made by taking A=0.86. Otherwise, A must be determined by tests on notched tensile tests.

4.3. Evaluation of elastic follow up factor r.

In order to be used in the design rule, it is necessary to have values of r for a wide variety of mechanical structures available in handbook solutions. In the case of notched specimens, these parameters can be evaluated according the equation (11) and using the

results given by the tests or numerical simulations for the same imposed displacement. The input data are therefore σ_e, σ and ε.
This parameter r increases when plasticity effect is more important and as a function of loading.
For plastic instability, it is worth noting that, for the annealed material, the r values obtained, are ranging between 4 and 7. For hammered materials the r values are located between 6 and 11 and are not very affected by these 3 hammered rates. A conservative value for AE configuration independent of R value, could be 5 for annealed material and 11 for hammered material.
For the rupture, the σ_e values are located in the range of 30000 and 5000 MPa. The r value are ranging between 6 and 15 and are not very sensitive to the hammered rate.

4.4. Evaluation of reduction of ductility

The results calculated in paragraph 4 can be used to evaluate how the reduction of ductility influences the design rules available for ductile material.
In the case of an imposed displacement, here considered, the limit value is given by the value of σ_e for each different configuration. The elastic follow up factor r is also available.

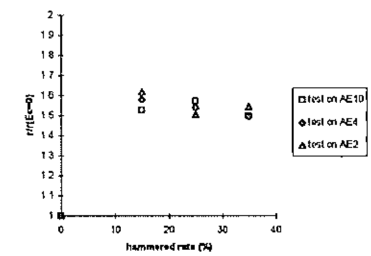

Figure 6 : Evolution of r value at instability versus hammered rate.

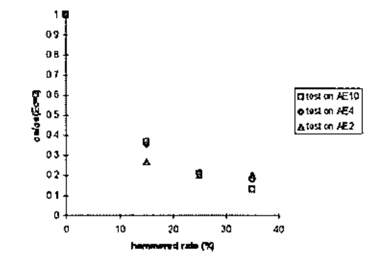

Figure 7 : Evolution of σ_e value at instability versus hammered rate.

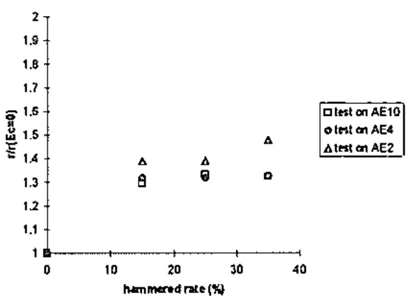

Figure 8 : Evolution of r value at rupture versus hammered rate.

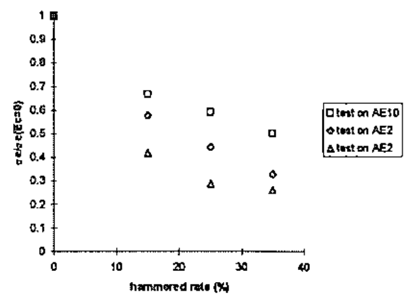

Figure 9 : Evolution of σ_e value at rupture versus hammered rate.

The Figure 6 and Figure 7 gives the evolution of normalised σ_e and r considering the values defined for annealed ductile material for the instability condition. These figures indicate that r can be increased almost by multiplying factor of about 1.7 and σ_e reduced by a factor of 0.1.
The Figure 8 and Figure 9 give the evolution of normalised σ_e and r considering now the rupture condition. The same proportion of increase of r and decrease of σ_e can be applied

for rupture condition. These four figures suggest that the reduction of ductility for these materials is real but is not catastrophic.

5.CONCLUSIONS

Usual design codes [3, 4, 5] put forward limitations only on primary stresses (which suppose a sufficient ductility of the material) and do not take explicitly into account the ductility reduction during the life of the material. The aim of this study is to propose complementary rules to evaluate this reduction in the case of a mechanical structure close to a screw configuration subjected to an imposed displacement. The material under study is 316L stainless steel quench annealed with different controlled strain hardening levels (from 0 up to 45%). Mechanical properties evolve with hammering in the same trend as irradiation. Tests (tensile tests on smooth or notched specimens) have been carried out for quench annealed and 15, 25, 35, 45% hammered 316L. We can notice the same macroscopic mechanical behaviour for hammered 316L at 20°C and irradiated 316L at 250°C. We have used this similarity of macroscopical mechanical behaviour in order to evaluate the influence of ductility on design rules. The proposed limits depend on mechanical properties as determined by tensile tests. In this study, we have proposed rules to prevent plastic instability and failure by ductility exhaustion. These rules have been adapted for an initial elastic analysis. The elastic follow up coefficient r is included in order to correct this elastic stress. The limit values obtained for hammered materials are in the same order of magnitudes as for the ductile annealed material. The elastic follow up parameter is increased by a factor limited to 2 value.

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